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FINAL REPORT

FEASIBILITY STUDY OF A CENTRIFUGE EXPERIMENT FOR THE APOLLO APPLICATIONS PROGRAM

VOLUME III

EXPERIMENTAL REQUIREMENTS FOR THE SPACE RESEARCH CENTRIFUGE

GENERAL DYNAMICS
Convair Division

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LANGLEY RESEARCH CENTER

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ABBREVIATIONS

AAP	-	Apollo Applications Program
ADH	-	Anti-Diuretic Hormone
AFB	-	Air Force Base
B. P.	-	Blood Pressure
C. A.	-	Cross-coupled accelerations
cc	-	cubic centimeters
cfm	-	cubic feet per minute
CLL	-	Central Light Loss
CM	-	Apollo Command Module
CPG	-	Capacitance Plethysmograph
CPS	-	Cycles per second
ECG	-	Electrocardiograph
EKG	-	Electro-cardiogram
EOG	-	Electro oculogram
EVLH	-	Egocentric Visual Localization of the Horizon
ft	-	feet
G, g	-	Gravities
G_x	-	Forces in the direction of the test subjects "X" axis (Front to rear)
G_y	-	Forces in the direction of the test subjects "Y" axis (Side to side)
G_z	-	Forces in the direction of the test subjects "Z" axis (long body axis)
GD/C	-	General Dynamics/Convair
H. R.	-	Heart Rate
IMBLMS	-	Integrated Medical and Biological Laboratory Instrumentation Measuring System
INST	-	Instrumentation
LBNPD	-	Lower Body Negative Pressure Device
LM (LEM)	-	Laboratory (Lunar) Module
LRC	-	Langley Research Center

ABBREVIATIONS (CONTINUED)

MCRD	-	Man-Carrying Rotation Device
MDA	-	Multiple Docking Adaptor
MIN	-	Minute
MSC	-	NASA Manned Spacecraft Center (Houston)
NA	-	Not Applicable
NAMI	-	Naval Aerospace Medical Institute
NASA	-	National Aeronautics & Space Administration
NVDI	-	Non-Visual Directional Indicator
OGI	-	Oculogravic (Oculogyral) Illusion
PCG	-	Phono cardiogram
PLL	-	Peripheral Light Loss
PMTC	-	Peceptual Motor Test Console
PP	-	Pulse Pressure
R	-	Radius
RATER	-	Response Analysis Tester
RFP	-	Request for Proposal
RPM	-	Revolutions per Minute
S-IV B	-	Third Stage of Saturn V Booster
SEC	-	Second
SRC	-	Space Research Centrifuge
TV	-	Television
vhf	-	Very High Frequency
VOG	-	Vector oculogram
ZCG	-	Impedance Cardiogram
ZPn	-	Impedance Pneumogram

RELEVANCE OF T-010 EXPERIMENTS TO SPACE FLIGHT PROGRAMS

Original Requirement

The "Space Research Centrifuge" was originally proposed as an on-board internal device which would be used periodically to expose the crew to a centrifugal force (Reference 1). It was hypothesized that such an exposure would prevent atrophy of gravity-stimulated organ systems. As such, the internal centrifuge would substitute for the much more complex system of a spinning station and would allow the zero g experiments to be performed without the complication of a counter-spinning hub.

Considerable empirical evidence has been obtained in the laboratory that such periodic treatment would support the cardiovascular system (Reference 2). Further experimental work has shown that this protection is probably mediated by preventing a change in circulatory blood volume. The Gemini flights, however, have also been completed since the original proposal and it has been demonstrated that the crews were able to withstand fourteen days of weightlessness plus restricted activity without serious loss of orthostatic tolerance. On this basis it can be reasonably postulated that an exposure of twice the duration of the Gemini flight can be tolerated without severe consequences (Reference 3).

If this were the only justification for the centrifuge, its requirement would not appear to be nearly as urgent as was once purported. In fact, to date there exists no definite experimental evidence that man cannot endure very prolonged exposures to weightlessness. All apprehension is based on apriori reasoning and even this is focused not on man's ability to survive weightlessness, but rather on his ability to cope with the re-entry acceleration and the normal earth gravity following re-entry.

The internal centrifuge is no longer justified solely as a support requirement. The use of such a device as a research tool to determine the problems of prolonged missions of periods amounting to years instead of weeks is gaining support, and its relevance to design of future spacecraft will be explored in this section.

Present Concept

The biologists' concern for man in space and his re-entry capability stems from the surprising adaptability of the organ complex to whatever environment is imposed upon it. This habituation process is the elimination of non-essential elements and the hypertrophy of supportive organs. It is

demonstrated by the polycythemia found at altitude, decreased salt content of perspiration in the desert, altered circulation patterns in the cold, the increased heart capacity of the athelete, and in the bone atrophy of an unused limb. Exposures to null gravity of sufficient duration to encompass the time for complete replacement of the tissue in any organ system might then be anticipated as having dire consequences to the body as we presently know it in the one-g system. These changes in zero-g cannot be thought of as detrimental, but only as normal for that environment. The important information required for future space flight is to know what the extent of these changes will be, at what rate they occur, and how they can be reversed or controlled.

An orbiting centrifuge, among other purposes, offers considerable potential for measuring these changes early enough in their process that rates may be determined before an operational problem develops for re-entry. The original purpose of the centrifuge, to support and to train for re-entry, has now become only one aspect and is included in a long list of possible space experiments that would be desirable for an advanced space station concept. The "Space Research Centrifuge", the T-010 experiment, is purely investigative in purpose, and the experiments that have been selected are for emphasis of design requirements. In the present study those areas of research that seem to impose the greatest complexity to the centrifuge were selected so the feasibility of such a device can be assessed in the most stringent manner. It is, therefore, important to the study concept, to also discuss the experiments proposed in light of their relevance to future space flight, for not all of those in the current list need be included in the first forty-five day schedule as has been developed in the time line analysis. It is anticipated that other experiments will be proposed that could be much more urgent in nature than the present list. Such experiments could develop from information obtained on the S-IVB workshop (wet or dry). The animal experiments for that study will (under current proposed scheduling) be completed before the first SRC is available.

Program Schedule

Information presently available indicates that the Apollo program will be partially concurrent with an orbiting space station program to encompass the objectives of Apollo Applications Program. The use of Apollo components to exploit the large space of a spent or dry launched S-IVB as an experimental laboratory appears to be rapidly approaching a program basis. It also appears that an additional space station of more advanced design will follow such a cluster arrangement. For planning purposes, the S-IVB workshop concept is anticipated for the 1969 - 1972 period and the advanced station would follow in 1973 to 1975.

This feasibility study for the Space Research Centrifuge indicates that the centrifuge would not be available as flight hardware until the 1971 or 1972 period. The various configurations studied show that the SRC could be attached to the S-IVB cluster at the Multiple Docking Adapter (MDA), in the same manner as the Apollo Telescope Mount, late in the S-IVB mission. The centrifuge design also conforms to use as an internal station facility should it be more applicable as such in the advanced Orbital Workshops or space stations.

The SRC concept includes the development of a ground prototype facility that is to be used first for engineering testing and, secondly, for experimental development. During that portion of the SRC program the S-IVB workshop would be in orbit. The T-009 (primate) experiment will be providing information about changes occurring in monkeys after a year's exposure to zero g, and the Integrated Medical and Biological Laboratory Instrumentation Measuring System (IMBLM) experiments will be correlating those changes with the reactions of space crews exposed up to 56 days. In addition, preliminary measurements will be in process to determine the reactions of the vestibular system in zero g during those missions. All of these measurements will have direct consequences on the requirements for the SRC. Should it be found that no problem exists and that the support devices used for the crew, such as lower body negative pressure, exercise, et cetera, are adequate and that no additional experimentation for inertial support is required, that portion of the SRC program could be deleted before the space device is built.

The more likely possibility, however, is that the S-IVB experiments will raise additional questions about the requirement for inertial support and, in that case, the facility has had two years' design work behind it. The program can then be included in the advanced station or, if more urgent requirements are found, the program could be accelerated to attach SRC-LM onto the S-IVB cluster MDA. Such an alternative would be indicated if serious consideration for an artificial g system were to result from the T-009 and IMBLM S-IVB workshop experiments.

Identification of Baseline Experiments and Order of Importance

The T-010 experiments will be described in detail and their physiological significance discussed in a later section. It must be realized, however, that this is a tentative list developed for purpose of design and feasibility of scheduling. The experiments chosen represent the three types of efforts that may be required if nothing startling or unexpected develops from the 56-day zero g exposure of man. It is anticipated that NASA will

want to know more about means for measuring orthostatic tolerance at various points of prolonged exposure, providing support prior to re-entry, and defining the problems to be incurred in an artificial gravity system.

For that purpose the proposed T-010 experiments can be ranked in importance as they affect the design problems that are likely to be concurrent at the time, these are prolonged exposures to 1/6 g on the moon or two years exposure to zero-g for interplanetary missions.

Ranking of experiments has been based on the following precept of experimental importance:

a. To acquire information pertinent to design of advanced space vehicles and to mission planning,

b. To determine better ways of supporting man in a zero-g environment, and

c. To advance the general scientific knowledge in experimental areas that cannot be duplicated on earth.

The experiments considered are all of a biological nature and it could easily be that one or more of the physical experiments to be considered later would supersede this list.

Advanced Vehicles and Mission Planning. - The Lower Body Negative Pressure Device (LBNPD) is currently believed to provide support required for the vascular system in zero-g. It has been demonstrated to increase the peripheral circulatory volume and thereby should maintain the circulating volume presumably through the Gauer-Henry reflex which is mediated by ADH production. It is also a good substitute for a tilt table as it provokes the same type of syncope reaction. Exercise should provide the necessary muscular support, as well as maintaining vascular tone and contributing to the skeletal stress that is required for bone stabilization. The amount and adequacy of support distribution, however, is difficult to anticipate. The possible observation of greatest importance on the S-IVB workshop to mission planning and advanced vehicle design would be the occurrence of uncontrolled loss of calcium from the skeletal system. The exercise methods to be employed such as the bicycle ergometer, elastic restraints, et cetera, require crew time and decrease efficiency. If it is found that additional emphasis is required for skeletal support, it could make an artificial gravity system more desirable. It may be that station spin-up is required only for a reconditioning prior to re-entry, but it would necessitate a program

acceleration to gain knowledge about man's tolerance and performance under such conditions. The experiments that are proposed as being typical for measurement of factors important from this aspect are:

a. T-010E - "The Semicircular Canal Stimulation by Cross Coupled Acceleration". Some work will have been done on the S-IVB workshop and that information will affect the experiment design. The SRC will offer a sophisticated and controlled apparatus to expand results of the M-053. In an artificial-g station the crew would be aligned with the centrifugal force and be in the plane of spin. Side-to-side head turns will then cause a maximum amount of cross coupling because the motion will be 90^{o} to the spin plane. The amount of interaction between semicircular canals and otolith is not presently known. Earth studies on crew rotation tolerance using subject alignments similar to the space station orientation have not been able to align the otolith correctly and these SRC studies will be the first opportunity to test this relationship. The cross-coupled acceleration is nearly independent of radius and results obtained on the internal centrifuge in space should be quite appropriate for use in design of a future artificial-g system.

A standard performance test can be used and the rate of head turn recorded in both the Z and Y axes. When the head is at the center of rotation, the otolith should have a zero-g stimulus; however, when the head is at a maximum radius, the otolith will be stimulated at an increased rate proportional to the square of the rpm. From this test, the interaction of the semicircular canal and otolith can be assessed.

b. T-010F - "G-Sensitivity". The sensitivity to linear acceleration will also be dependent upon the otolith activity in artificial-g. The stability requirements for a rotating station will depend largely on this organ sensitivity. Testing for the threshold levels of this organ has so far been limited to one-g and above. It is probable that an artificial-g system would not have to duplicate the one-g conditions to adequately support the physiology of concern so that these measures will have direct application to advanced vehicle design - should the requirement for such a system be established.

Crew Support. - A second possible result of the S-IVB studies would be decreased re-entry tolerance of the crew. Of particular importance in this aspect is the "off-nominal" re-entry where optimum g-alignment is not preserved. Such a reaction would indicate that the vascular support devices had not worked to the anticipated level and that the therapeutic (G_Z) centrifugation and the testing of that treatment by grayout, tilt table, and re-entry

simulation on the centrifuge was desirable.

These studies could compare the value of the centrifuge procedures with LBNP and determine how the G_Z, or therapeutic experiment T-010B, could be most efficiently employed. The mechanisms involved are discussed in the Experiment Development section. In brief, it is to: first, reinstate or maintain an adequate circulatory volume for re-entry and, second, to maintain a vascular reflex response so the circulatory volume can be shunted to the central portion of the system rather than the periphery. It is likely that this treatment can be done during the week prior to re-entry and conserve time for other tasks during the mission. The grayout T-010A and tilt table experiments are means to assess the requirement for the therapy during the mission rather than waiting until a problem develops. For investigative purposes it would be desirable to apply G_Z intermittently throughout the mission in one experiment group, and in a second group apply the therapy after some decrease in orthostatic tolerance was indicated by the grayout or tilt table tests.

The Re-entry Simulation T-010G is a means for ensuring the crew's ability to re-enter. It will also be considered under a later section as a means of assessing performance. The advantage of this test is learning how well re-entries will be tolerated.

Scientific Knowledge. - Orbital experiments offer the advantage of learning how biological systems respond in zero g. Adequate control for such experiments, however, is difficult without some level of acceleration in space. In addition, the centrifuge adds the capability to investigate pure angular acceleration without a g-vector involvement. The T-010C experiment that measures the canal threshold sensitivities without the possible otolith bias is an example of this category of experiments.

Physical Experiments

Many of the mechanisms and processes involved in the life support system and station keeping involve g-dependent phenomena. The SRC provides a means to measure with great precision the curve of g-dependency. The man in the couch can perform a bench experiment repeated at various g levels. These experiments fall into two general categories: basic processes and component evaluation. In a recent contracted study (NAS 1-6939) some ninety-two life support system processes were analyzed and sixty-nine were found g-dependent. Most of these could be handled by designing around the problem. However, such "technological fixes" assume all factors have been considered, which is not always true. The gas-liquid

separation is an example that has had considerable design attention; yet reliable operation has not been achieved when the devices are tested at zero-g. The SRC offers a means for qualifying such designs. The other area for experimentation is the investigation and formulation of equations for processes that may not have a continuous g dependency. Flame propagation, liquid mixing, and fine particle behavior are examples of experiments where one-g and zero-g do not provide all the desired information. The SRC can be used to fill this type of information gap and assess and determine the value of artificial-g for systems operation in interplanetary missions.

Additional Use Concepts

Experiment selection for purpose of design of the SRC was considered primarily from the physiological aspect. Performance measurement is another area of potential use that is equally important. The re-entry experiment involves performance testing,and the analysis performed on the use of the SRC as an assist to waste collection demonstrates its use as a support component. Many assembly and repair tasks have been postulated as being difficult in zero-g or have been used as support for the artificial-g station. Such support advantage can be statistically evaluated on the SRC by finding the optimum g level for such assembly tasks performed on the spinning couch.

In addition, the centrifuge provides a convenient and accurate means of mass measurement of crew members or of any orject in the same relative mass range which may be attached to the couch. This is accomplished by the installation of force sensors at the couch attach points and recording centrifugal force on the couch at two different radii. This technique, which is described by Reference 41, eliminates the need for locating the exact center of mass of the subject being weighed.

The cluster concept of attaching the SRC on the MDA produces a capability that could be used for an extension of the T-009 primate program. After completion of the manned testing program, the facility can be adapted by replacing the couch assembly with a cage module for primates or other mammals and maintaining them at one or more levels of artificial-g. A small acceleration will greatly reduce the complexity of animal husbandry in space, and as much or more can be learned about the physiological -g dependency at low-g levels than at zero-g because a response curve can be established rather than the all-or-none approach. (See Figure 1).

Importance To Future Space Systems

Interplanetary missions in the 1990 period will offer an opportunity to greatly expand all aspects of space research. Experimentation as well as system design will have to be carefully examined for objective and puspose. Prior to those missions, the capability of a crew to work under the one-half g of Mars after six months of

weightlessness will have to be determined, and the means of rehabilitation under earth orbital conditions after an additional one and one-half years of weightlessness should be explored in the orbital space station program. An artificial-g station is usually included as one of the possible solutions for interplanetary travel, but it presents many complications in vehicle pointing and course correction. Prior to design of an artificial-g station, a great deal more should be learned about its advantages and disadvantages in an experimental spin-up of a test station, but that also calls for a mission program of considerable effort and it can be preceded by research programs using an orbiting centrifuge to create realistic environmental parameters which will be found in systems incorporating artificial gravity. The Space Research Centrifuge appears to be a means to achieve such operational approaches at minimum cost and crew risk.

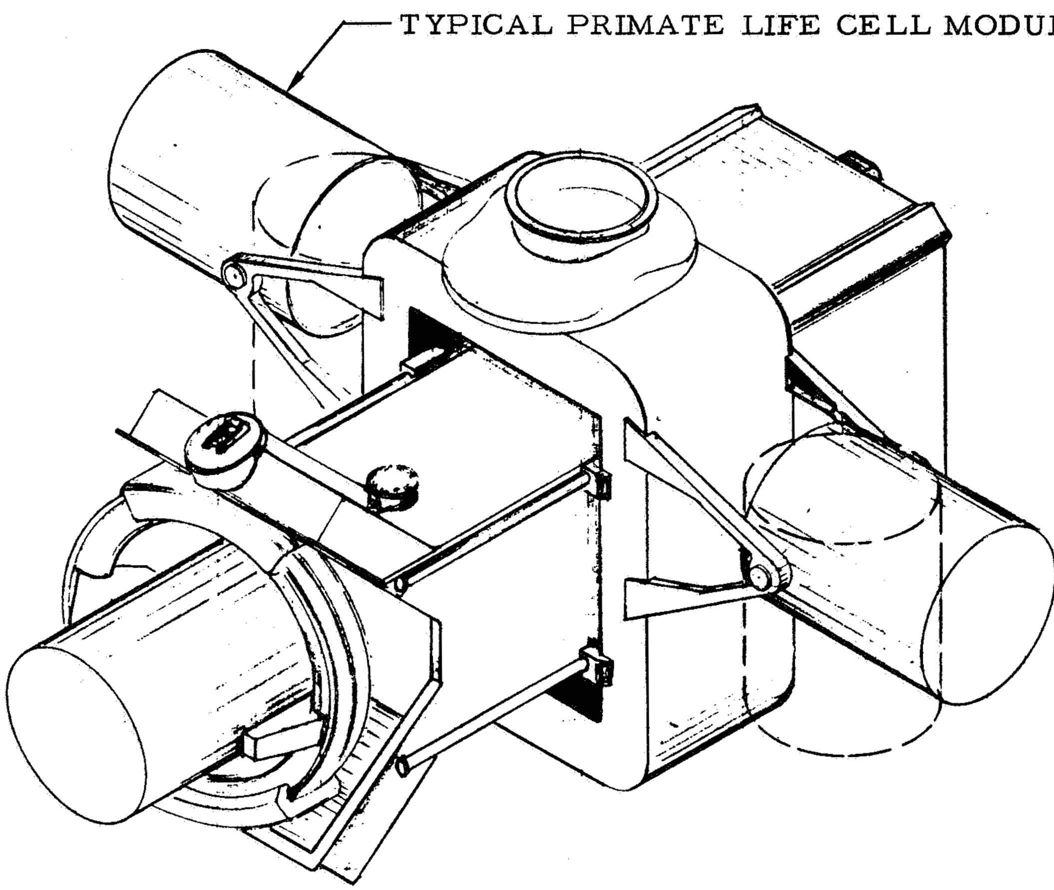


Figure 1, - SRC Modified for extension of the T-009 Primate Program.

PURPOSE OF STUDY

Centrifuge Serves As An Experiment Test Facility

The deliverable item for this contract is a preliminary design for an engineering test prototype to evaluate the feasibility of a space centrifuge which would be orbited in the AAP Program, using either the S-IVB workshop or a modified LM laboratory as the support vehicle. The engineering test facility would ideally serve to provide some baseline measurements on the reaction of human subjects to the accelerations imposed by the simultaneous and multiple accelerations used in the space experiment program. The centrifuge structure itself provides the angular velocities and accelerations in one plane. This is the primary motion of the centrifuge. The subject interfaces with the centrifuge by means of the couch restraint system. It is the couch restraint system which provides the correct orientation, secondary angular velocities and accelerations, and the manipulations required to investigate the subjects' response to being moved through this inertial environment. It is, then, the couch assembly which provides the immediate experimental measuring capabilities for the mission, and it is into this couch that the instrumentation for these measurements must be incorporated.

Centrifuge Couch Interface

Couch Requirements. - The centrifuge design is to be applicable to both the LM laboratory and the advanced workshop S-IVB concepts currently being evaluated by the AAP Program Office. The vehicle installation decision affects the basic centrifuge design considerably more than it does the couch system, for in either case the couch restraint manipulative capabilities will be common. Only restrictions on swept volumes would greatly affect the decisions about how the couch should be designed to provide proper orientations. The S-IVB vehicle would allow a greater radius and, as such, might slightly change the experimental approaches. To define the couch requirements adequately it is necessary to know what experiments are contemplated and to determine the tentative protocol that will be used to achieve the desired measurements in these experiments. At the present time the eight experiments suggested in the original RFP, plus those two which have been developed during the study contract, are all of a very tentative nature. It has been necessary, however, to make certain assumptions about the approaches that would be used by principal investigators for each of these experiments to begin the study of design trade-offs.

Background Of Centrifuge Design And Evolution Of Experiment Requirement. - The feasibility of including a short radius centrifuge in a manned orbital laboratory was proposed early in the space program by Dr. W. J. White. The purpose of the centrifuge on the vehicle was primarily as a substitute for an artificial gravity system. It was proposed that periodic exposure to the linear accelerations created by such a centrifuge would reinforce man's tolerance to a re-entry situation following prolonged exposure to weightlessness. In addition, it was proposed that such a centrfuge could provide a means for assessing the rate of degradation in performance of re-entry tasks due to zero-g exposure. These possibilities were investigated and shown to be feasible in a series of studies by Dr. W. J. White, J. W. Neiburg, R. H. Grimes, L. M. Finney and others. With the advent of the Apollo Applications Program, the desirability for a space-orbiting centrifuge has been increased. The emphasis no longer is placed upon the therapeutic and re-entry simulation uses, but has been expanded to include a general purpose space laboratory to investigate man's sensitivity to linear acceleration, angular accelerations, cross-coupled accelerations, and gravity gradients at zero-g. A centrifuge in space offers the unique possibility of studying pure angular accelerations without the complications of a linear acceleration or g force compounding the data interpretation. Such an environment can be used to study the physiology of the labyrinthine organs.

Problem Of Space Simulation For Baseline Measurements. - It is the unique capability of being able to produce pure angular accelerations within a zero-g background afforded by the space centrifuge that makes it extremely difficult to create comparable control situations on earth. The early space centrifuge can, however, be used to assess the artifact of the gravity vector in ground simulation studies. On earth, centrifugation creates a resultant vector. The resultant is composed of the 1-g acceleration summated with the centrifugal force created by the angular velocity of the centrifuge. In space it is possible to align the body axis (Z axis or spin) along the radial direction which is parallel to the centrifugal vector and, at the same time, be in the plane of spin. When an angular motion is made in a rotating environment there is a cross coupling of angular velocities produced, which results in a torque aligned in a plane orthogonal to the other two planes of rotation. This torque becomes maximum when the motion is made perpendicular to the plane of rotation and minimal when made in the plane of rotation. On earth then it is possible to align the Z axis of the body (spine) along the gravito-centrifuge vector as it would be aligned with the centrifugal vector in space, but any head motions or body rotations made in such an orientation will produce different couplings than it would in the space situation. The simulator can provide reliable data concerning engineering design and mechanism operation, but cannot be used for complete simulation of the space experiment, consequently any baseline data derived from such a

simulator must be interpreted with utmost caution. Within the constraints of such a cautious approach it is possible to study certain inter-relations which are dependent purely on cross-coupling of angular accelerations or reactions to linear acceleration. These include such phenomena as oculogyral illusions and the cardiovascular responses to high-g gradients.

Engineering Test Simulator And Requirements For Use As Baseline Earth Responses. - The first requirement to dictate couch design is a limited baseline measuring device. If the prototype is to be used purely as an engineering test device, the couch does not require a degree of freedom which will take it out of the plane of spin. However, if the simulator is to be used to study man's responses to the space experiments on earth, it is necessary to align the long body axis of the man with the resultant gravito-centrifugal vector. This requires that the couch have the capability of being oriented out of the spin plane. Experimental procedures to date have attempted to keep the man in the plane of spin for the orbiting situation in order to decrease the hazard of nausea produced by cross coupling.

Position Control and Precision

Physiological Limits. - Two major constraints are imposed upon acceleration characteristics of the centrifuge; these characteristics are centrifugal force and angular velocity. The limitations for centrifugal force have been quite well demonstrated in the Douglas studies and act predominately through the cardiovascular system. The limitation is cerebral ischemia that results from forcing the blood away from the area of the brain, and petechial hemorrhage from excessive pressure in the feet. Obviously, the g level at which this occurs depends upon the orientation of the subject. The most effective situation for pulling the blood away from the brain is with the subject aligned along the resultant vector and his head close to the center of rotation. This situation in space can be quite well simulated on earth. However, the second limitation, that of labyrinth disorientation which results in nausea, vomiting and sometimes in syncope (fainting), is not so easily duplicated as discussed in the previous paragraphs. The non-acoustic labyrinth can be divided functionally into two parts. The semicircular canals consist of three fluid loops medial to each ear and act as angular accelerometers in approximately three orthogonal planes. The mechanism is roughly similar to a fluid transducer working upon a torsion pendulum. Inferior to each of the semicircular canal systems are the otoliths. These organs, again, act similarly to an inverted torsion pendulum but, in this case, are responsive to gravity much in the manner of a blumb bob. The anatomy and physiology of these organs are just now being revealed and in the past have received attention by comparatively few physiologists. Both organs assist in spacial orientation and their outputs are integrated with the vision and proprioceptive senses. An individual's orientation experiences are recorded centrally through coordination of the impulses from these three sensory systems. The memory of these coordinated signals allows

unconscious adjustment of body position within the gravity oriented field on earth. Two of these sensory inputs will be altered in the zero-g situation. The proprioceptive senses and the labyrinth respond to stimuli created by the g field. Whenever one of the three of these inputs deviates from the usual association, the sensation resulting is bizarre and the individual responds with an increased sympathetic activity. Many responses of spacial orientation are reflex in nature, and a spurious impulse to the nervous system will create an established reflex normally associated with that stimuli and results in uncontrolled eye movement or loss of balance through disorientation.

Vehicle Stability. - Control of centrifuge motion must be sufficiently precise to avoid artifacts elicited by cross coupled accelerations other than those being experimentally induced. Threshold sensitivities for the angular acceleration detection by the semicircular canal are currently being investigated by Clark and Stewart at NASA Ames Research Center and have been estimated by others in the past to be greatly variable from individual to individual. Most measurements have been made about the Z axis rotation and minimum thresholds of $.03^o/\text{sec.}^2$ acceleration have been reported. In some individuals, however, this apparently is as high as $8.5^o/\text{sec}^2$. Clark and Stewart (1967) report coupled threshold values equivalent to 4 to $6^o/\text{sec}^2$. In Volume IV of this report, cross coupled accelerations as low as $3.6^o/\text{sec}^2$ are reported. Linear acceleration rates have not been as well defined and there exists a certain amount of confusion in the terminology. The normal function of the otolith is to determine tilt rather than magnitude of acceleration. From Graybiel's work (1955) it appears that lateral forces of .02 g can be detected in 75 per cent of the subjects exposed. This corresponds to a tilt angle of approximately 1.5^o from vertical. Roman, et all., and others have exposed subjects in elevators to varying g levels along the Z axis and observed resulting illusions of vertical displacement. However, thresholds for such illusions were not defined. These liminal values are of considerable importance in the experimental design for the centrifuge, and they determine the required control and precision of the driving mechanism. In addition to these thresholds, another factor that has received essentially no quantification is the liminal values for cross-coupled accelerations resulting from the possible combinations of angular motion, time of motion and orientation within the coupled field force.

In many types of labyrinthine experiments, apparent motion either of an external object or a feeling of bodily displacement is used as the criterion for liminal stimulation. It would be difficult to separate the sensation due to cross coupling from that of any other motion imposed upon the subject. It is fortunate that angular thresholds are apparently lower than the threshold for cross coupled or Coriolis angular detection as this makes small vehicle instabilities experimentally acceptable.

It is possible however that cross-coupling might interfere with other physiological systems such as the sympathetic responses imposed by tilting the individual with respect to the centrifugal force. It can be anticipated that two basic types of criterion would be involved for cross-coupling at high spin rates: (1) sensation of movement and (2) degradation in performance.

Null Gravity. - The sensitivity of the vestibular system under zero-g conditions is not known. A modulation effect upon the semicircular canals by the otolith has been postulated as either a direct (fluid) coupling or by central neuro-integration of signals. If this is true, then it might be reasonable to presume an increase in sensitivity for detection of angular accelerations at the null gravity situation. The thresholds for detection of angular acceleration rates might also change as the otolith activity becomes accustomed to the new zero-g environment. It seems advisable, therefore, to insure control and precision for the centrifuge which is an order of magnitude beyond that which has been shown to be detectable under earth conditions. It is also important that liminal values be obtained for the product of cross-coupled angular velocities, and linear velocity as a function of angular velocity (Coriolis) for those situations anticipated during operation of the SRC.

Positioning Rate

The design rates for couch motions should be no more than half the liminal or tolerance value. The tolerance rate is that angular velocity which could be anticipated to cause stomach awarness that normally precedes nausea. The liminal or threshold is the lowest detectable stimulus which could alter the end point being measured. In no instance are tolerances considered those rates which would elicit vomiting. In addition to cross-coupled angular acceleration, another stimulis to the semicircular canals must be considered. On a rotating centrifuge, a radial velocity will cause a Coriolis effect that can be anticipated to complicate experimental interpretation. Though this is an important consideration, little data is available to establish the relationship between the ability of angular and linear velocity to elicit a response.

Extent Of Couch Motion Freedom

Single Plane Vectors. - Confining all couch orientations so that the plane of movement is in the plane of spin reduces the chance of problems from cross-coupling. This, of course, is not possible in the case of the ground-based centrifuge where alignment with the gravito-centrifugal vector is

required. One of the classical methods for investigating the otolith is the use of the "oculogravic illusion" (OGI) that results when a lateral force is imposed by centrifugation upon the ever present gravity vector. An individual with restricted vision has the illusion that he is being tilted in line with the resultant vector. This is due usually to a combination of the centrifugal force and the force of gravity. In space it is not easy to simulate this situation. On the centrifuge only centrifugal forces due to angular velocities can be generated. A man placed at right angles to the spin plane during rotation at a constant rate under space conditions may not perceive an illusion of tilting but rather a sensation of being accelerated radially. This would not be usual oculogravic illusion. By having complete capability of positioning on the centrifuge, however, it may be possible to create the sensation of oculogravic illusion during a "burn" period when the vehicle is accelerating providing the centrifuge could be operated simultaneously. It is doubtful if the effort involved, however, would be justified by the significance of the data.

Limited Experimental Freedom. - Additional experiments are to be submitted by other investigators. It is also probable that proposals will be submitted which will require motions out of the plane of spin. The tilt table facsimile to be considered as an experiment is presently designed to move the man in the plane of spin. It is possible to do this experiment with the man lying parallel to the rotation axis and then being tilted at an angle to it. Such an arrangement would have the man more closely arranged to the tilt table situation on earth as all points on his body would have equal g values when he is oriented parallel to the axis.

Conventional Aspects Of The System

Couch Instrumentation. - The instrumentation required for experimental measurement may be integrated into the couch or attached for each experimental procedure. The weight and volume increases that the instrumentation imposes will determine the procedure to be followed. In general, all bio-sensors which add little in the way of weight or volume should be integrated into the couch mechanism itself and a volume should be allowed for such purposes. It is necessary to review the general types of equipment required for possible experiments so that adequate attachment parts and fixtures may be integrated into the couch design. It is also necessary that the weights of this equipment be considered in the counter-balance arrangement. Much of the instrumentation to be used will not be decided until the final Experimental Implementation Program has been completed. This necessitates keeping the system flexible so various arrangements can be tested on the ground-based centrifuge when it becomes available.

Centrifuge Enclosure. - The location of the centrifuge system in the LM complex is now assumed to be as shown in Figure 2. However, from certain safety aspects it would appear desirable to enlarge the centrifuge housing so the experiment monitor would have better access to the subject when he is in the couch of the centrifuge. The location of the centrifuge S-IVB workshop allows such accessibility but is complicated by some of the present concepts for a tunnel design in the center of the S-IVB work shop. The tunnel arrangement requires that the centrifuge be mounted on the far end of the vehicle close to the liquid oxygen tank. In either case, a requirement for the couch to be aligned normal to the spin plane would greatly increase the space requirement for the centrifuge complex and does not appear warranted in the space vehicle.

Expansion Capability

Waste Collection. - It has been proposed that the centrifuge availability could facilitate the management of waste collection. This concept appears to be quite feasible and has been analyzed as part of the contracted study. Orientation of the subject for this purpose requires considerable analysis, as the purpose is to separate the subject from the waste matter and collect the matter for eventual sampling and measurement in the most sanitary method possible. Any object not restrained on a centrifuge does not release along a radial trajectory but rather along a tangetial trajectory. In the case of waste matter, therefore, it would proceed along a tangent to the circle being circumscribed by the perianal region. Relative separation rates appear on first analysis to be independent of angular velocity, and it is desirable to maintain as low an angular velocity as possible. Sanitation procedures, waste handling and collection will require additional analysis to derive the best possible subject position for optimum sanitation and also a requirement for a knee joint on the couch.

Mechanical Testing. - Many of the mechanical designs which will be used for life support and experimentation will have g dependencies that can be defined by a man working within the centrifuge at various g levels. A workbench or some manipulation area would be required on the couch to facilitate such g dependent measurements and in this way evaluate the feasibility of an artificial gravity system for mechanical components. A very significant question at the present time for such artificial gravity systems is, " what g level is required for both man and optimal operation of mechanical systems". The centrifuge may be able to provide means of establishing some empirically derived estimates.

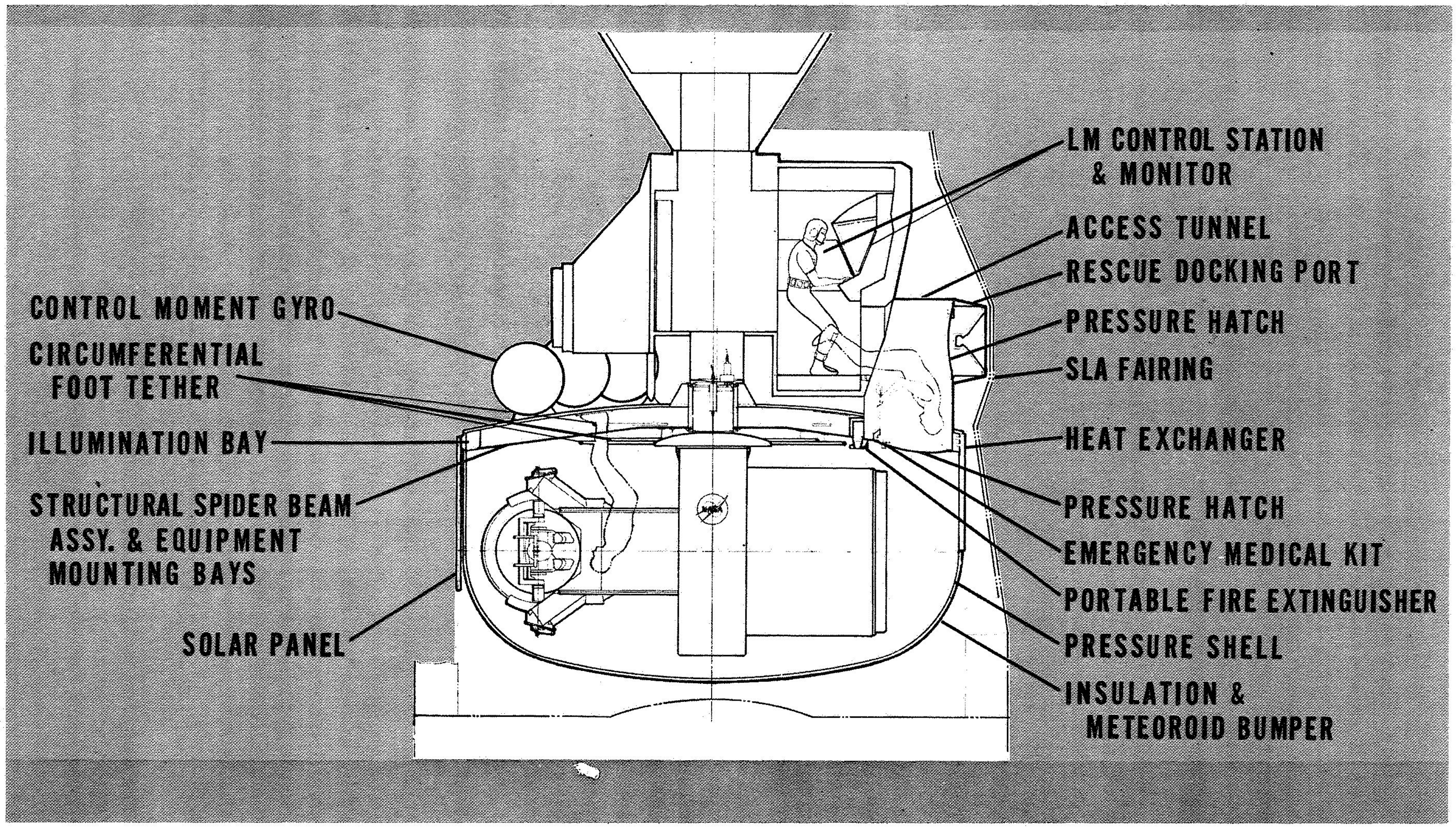


Figure 2. Centrifuge Location in CSM/ LM/ SRC Complex

EXPERIMENT DEVELOPMENT FOR T-010

Mission Program

The purpose of a space centrifuge is to make available a versatile experimental facility for the use of the general scientific community. In defining this facility, it has been the task of the designers to choose typical experiments which are diverse enough to provide the centrifuge with as many general capabilities as possible within reasonable limits for engineering, cost and time schedule. For this study, design has been based mainly on the candidate experiments stated in the RFP and details of the experiment protocols partially developed in order to support definition of the facility. It must be recognized that the present protocols are preliminary and that, once this facility becomes a reality, it may be anticipated that the scientific community will present many new concepts for its use which will further influence design.

Experiment Proposal. - To define the couch requirements it was necessary to analyze presently proposed experiments in considerable detail in order to examine realistic problems in centrifuge and couch design. When these experiments are firmly defined in detail, much of the information required to complete NASA Form 1346, "Experiment Proposal for Manned Space Flight", will be available and organized for experimental protocol assessment.

Experiment Division

Test Apparatus. - In the final design cost and time estimates for each of the experiments will have to be developed for the principal centrifuge experiments (designated T-010) in order to evaluate each procedure on its own merit. The centrifuge itself is an implement with which to do the various experiments and procedures rather than being an experiment itself. The basic cost of this implement cannot be reflected in any single proposed experiment. To circumvent the problem for the purposes of this contract, the T-010 designation is considered for the centrifuge complex itself, and the T-010A, B, C, et cetera are used to designate possible proposed experiments for use on this centrifuge. It is further assumed that the principal investigator and laboratory of experiment origin for T-010 would remain at the Langley Research Center. The individual experiments, however, would more likely have either a principal investigator or a co-investigator with an established reputation in the particular field of research utilizing the centrifuge in that one experiment.

Centrifuge Location. - The centrifuge itself, designated as T-010, is considered essentially the same whether it be included in the S-IVB workshop on the LM or incorporated into some other undefined vehicle. It is not anticipated that the vehicle in which the centrifuge is located would greatly influence the experimental approach, facility, or detailed procedures as long as the couch structure remains unchanged.

T-010 Experiments A Through G

The present scope of this study does not allow the depth of analysis necessary to complete Form 1346 for each of the proposed experiments, however, experiment objectives have been established and analyzed for subject orientations and required instrumentation in each case. The following discussion is presented for the purpose of (1) defining the background that led to the experiment objectives, (2) the problems in gaining meaningful data that can be interpreted to define the objective, and (3) in some cases to point out the information that is now lacking to complete the protocol for these experiments.

T-010A - Study of Grayout Thresholds by Use of Peripheral Vision Lights. - Background. - The Air Force evaluated the potential of an onboard centrifuge system and Piemme et al (1966) measured the duration of human tolerance to positive acceleration on a short radius centrifuge which produced a 256 per cent heart to foot acceleration gradient. They found that acceleration levels of + 1 G_Z, +2 G_Z and +3 G_Z(reference to the foot) were tolerated by all subjects for periods of two hours, however, one subject did become nauseated following head movements at a +3 G_Z environment. The subjects, using comparable levels of acceleration, were able to ride a short radius centrifuge of 4.75*feet for a longer time period than they could at a 23 ft.*radius. The steep acceleration gradient does not appear to reduce tolerance to positive acceleration. Air Force and NASA studies at Douglas investigated head to toe acceleration gradients of 20 to 219 per cent on short-radius (16 and 156 in.) centrifuges. These studies indicated that tolerance measurements are possible on short-radius centrifuges using low intensity peripheral vision lights and gradual onset to blackout. The Douglas (W. J. White et al, 1965) group also found that as radius decreases and the gradient increases there is a tendency toward increased g before blackout occurs. They did not experience the complications of sickness due to head motion in their studies. They did report complaints of discomfort and pain in the calves and feet of subjects who were exposed to their maximum levels of acceleration and who did not show the expected blackout. Using a low intensity central light loss as criterion for tolerance, the investigators at Douglas found that onset rate minimally affected the mean g level attained. At 156 inches from the heart,with a .2 g per second onset,the mean for CLL (central light loss) occurred at 3.9 g compared to 3.8 g at 3 g's per second onset. With a 16 inch radius to the heart, the mean level

*(referenced to the subject's foot)

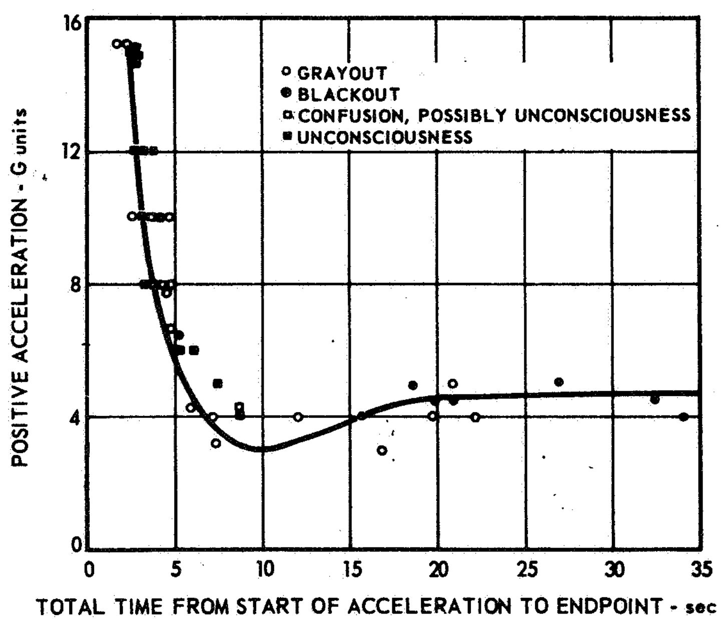
for CLL was 3.0 g. They also reported the effect of radius on g level tolerance: at a 30 inch radius to the heart the mean level attained was 3.6 g, at 58 inches 4.6 g, at 112 inches 4.4, and at 172 inches 3.9 g.

The use of centrifugation along the G_Z axis to re-establish entry tolerance, as well as the use of a tilt table to assess the effects of weightlessness degeneration, will be discussed at a later point. Acceleration tolerance, tilt table exposure, and the therapeutic experiments, as well as the re-entry simulation experiments, stimulate similar organ systems and can complicate experiment interpretation due to a supportive effect if more than one test is performed on the same subject. In general, a decresae in $+G_Z$ tolerance to acceleration is anticipated in space because of the change in circulating fluid volume. This is based on the precept that an increase in central circulating volume will cause a diuretic response. This response is mediated through an inhibition of the anti-diuretic hormone of the pituitary. Bedrest is known to cause such changes by diuresis, and space flights, to date, have shown a decreased circulating volume, presumably due to consequences of weightlessness. When blackout, either peripheral or central, is used as a criterion for acceleration tolerance, the mechanism of blackout is presumed to be dependent upon retinal blood supply. The efficiency with which the heart can supply the head with blood depends upon many factors. Sufficient blood volume to fill increased peripheral circulation during $+G_Z$ acceleration is one of the important factors. Repeated tolerance testing, however, will produce the same supportive effect that the therapeutic procedure is to accomplish.

Leverett and Zuidena (1960) have analyzed the problems of using peripheral and central light loss as a criterion for determining acceleration tolerance and point out the variability in technique that is found in the literature. The end points for acceleration tolerance will be even more difficult in space than the usual procedures on earth as total blackout or unconsciousness that closely follows would be undesirable under such circumstances. Some facilities have used white or white/yellow lights for central and peripheral lights, while others have used green for peripheral and red for central lights. This offers the possibility of deferring blackout levels due to dependence primarily on rod or cone vision respectively. The report cited also points out that some groups used peripheral light loss (PLL) as an end point. This loss is attributed to a decreased blood supply in the peripheral retinal area causing a decrease in angular visual fields. Other centrifuge operators have used a combination of PLL and central light loss (CLL). In the CLL situation blood is not reaching any portion of the retina and a complete loss of vision results. The increase in g per second has been found to be a highly significant factor in earth tolerance tests. A gradual onset centrifugal force permits greater reflex compensation. G onset should be a highly controlled factor in space even through the centrifuge experiments at Douglas indicate an increased g onset

tolerance for short radius centrifuges. T-010A on grayout will, therefore, be considered as not being finally defined and the centrifuge will be equipped with peripheral and central lights with variable intensity lighting. The experiment presently calls for lights being placed at 0, 23 and 80 degrees about the subject's head. The final choice of end point will be determined by the eventual principal investigator for the experiment with the use of the ground-based simulator.

Experimental. - Experiment to be performed on the 7, 14, 21, 28, 35 and 42 days. Two astronauts shall be subjects of this experiment. The subjects will be seated with the rotational force vector along the body ($+G_Z$), as in Figure 4. Accelerations to about 6 g's will be required. Lights at 0^o, 23^o and 80^o from the axis of vision will be used. The lights shall have a control to establish a specific illumination value. The tests will be brief, sufficient to record the times the lights are lost to the subject's vision. A specific rate of acceleration onset will be used. This is to be subsequently selected. For preliminary design, onset has been restricted to 0.1 g/ sec to maximize the period between gray-out and unconsciousness. From the graph (Figure 3) it can be seen that 4 g at slow acceleration allows gray-out and blackout without the danger of unconsciousness. This experiment will involve twelve runs during the 45 day period.



(Adapted from Stoll, NASA SP 3006)

Figure 3. Acceleration/Time Influence for Grayout Experiment

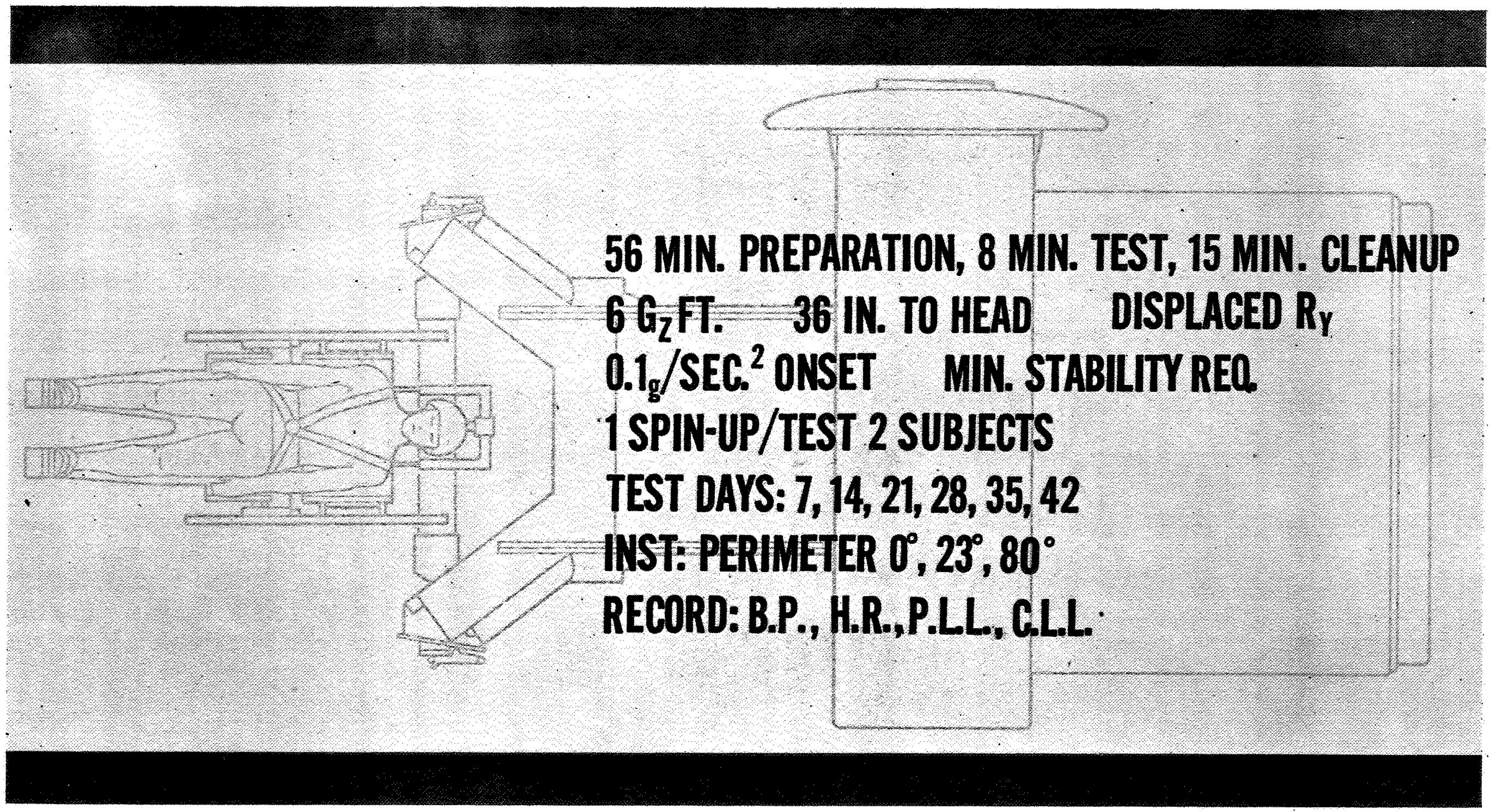


Figure 4. T-010A, Grayout.

T-010B - Therapeutic Support. - Background. - W. J. White and his co-workers pioneered the effort using an on-board centrifuge to maintain orthostatic tolerance for re-entry during prolonged space flights. A series of experiments by P. D. White et al (1965) and Nyberg et al (1966) demonstrated that a conditioning regime using a $+1.75\ G_Z$ (heart) for twenty minutes, four times each day, was sufficient to alleviate the anticipated deterioration produced by recumbency to 70^o head-up tilts maintained for 20 minutes. Syncope was reduced, and the orthostatic increase in heart rate produced on the tilt table in non-conditioned subjects was greatly reduced. The g time of 4.7 hours (g at foot level multiplied by total time) appeared effective and tolerable providing g levels remained below $.75\ G_Z$ (heart). It was found that a $+ 2.5\ G_Z$ (heart) level for twenty minutes generally exceeded the tolerance level.

Post-flight examinations of the Gemini crew members showed decreased tolerance to tilt table tests. These decreased tolerances were similar to those that had been previously observed in the Douglas recumbency experiments. It appeared that the degradation in the cardiovascular system was reflecting a lowered total blood volume. These changes have not been serious and should they continue, they would not be of serious consequence in prolonged flights. However, if the decrease in blood volume were to continue during more prolonged missions, serious deconditioning might result which would impair the capability for high-g re-entries. Piemme, McCally and Hyde (1966) examined the use of a short-radius centrifuge for possible in-flight support to the cardiovascular system. Their experiments consisted of water loading subjects and then determining how $+G_Z$ accelerations up to 3 g magnitude affect the expected diuresis. They found that free water clearance decreased with increasing g load from a control need of + 2.8cc/minute to -.5cc/minute at 3 g. They concluded that acceleration does impair the ability to excrete water and, further, that the response is mediated by the anti-diuretic hormone. This is explained on a basis of the Henry-Gauer blood volume control mechanism. Rogge et al have recently confirmed this conclusion by measuring ADH directly.

It is this control of blood volume that is to be accomplished by use of the on-board centrifuge. Blood volume control has recently been quite extensively reviewed by Gauer and Henry (1963). The postulated control system consists of atrial stretch receptors that are stimulated by an increase in central circulatory volume. These receptors in turn inhibit the output of anti-diuretic hormone through the vagus and reticular formation. Diuresis reduces the central blood volume. It is assumed that a subject in (1) bedrest, (2) exposure to negative pressure breathing, (3) water immersion, or (4) high G_X experience would then have an increased central circulating volume and diuresis would act to reduce the total circulating volume. Contrarily, an increase in ADH blood level would result from any condition which increased the peripheral blood volume and decreased the central blood volume, With G_Z plus acceleration, the peripheral pooling would stimulate anti-diuretic hormone, while G_X acceleration would tend to pool blood in the central area and cause diuresis. The mechanism of action is an important one to keep in mind during a total mission planning. While this experiment would tend to increase the blood volume for a successful re-entry, those experiments which impose a high G_X, such as the re-entry experiment, would tend to do the opposite.

A question remaining, and on which there is no available data, is whether it is required to maintain the centrifugation regime throughout the entire exposure to null gravity or whether it would be sufficient to simply increase the circulating blood volume with a therapeutic regime just prior to re-entry. The periodic stimulation of the pituitary could have actions on gravity-sensitive systems other than circulating blood volume, such as muscle and bone. In that case it may be important to maintain centrifugation throughout the entire mission. Such a decision will make significant changes in the power requirements throughout the entire vehicle system. For the purposes of this mission planning it will be assumed that the subjects will be exposed four times each day for twenty minutes to 1.7 G_Z (at heart) during the last ten days of the experiment. (This corresponds to 4.7 g hours in terms of 4 G_Z to the feet with a rate of g onset at .1 g per second). The subject will be positioned with his back on a radial line and the couch in the legs-up position. When the head is at 16 inches it will be at approximately 1 g, his heart at 1.7 g, and his feet at 4 g when the centrifuge is spinning at 54 rpm.

Experimental. - One Astronaut will be centrifuged at regular intervals during the 45 day mission. During each of the last 10 days of the 45 day period, a second astronaut who does not perform the re-entry stimulations shall perform this experiment. Each subject will ride the centrifuge four times each day for a period of 20 minutes each day. The maximum radius will be used with a rate of rotation to give 4 "g" accelerations at the feet. The inflight studies, as well as pre-and post-flight examinations will be used to determine the effectiveness of such exposure. This experiment will require 40 runs during the last 10 days of the 45 day period, and the orientation will be as shown in Figure 5.

T-010C - Threshold Levels of Sensitivity For Angular Acceleration. - Background. - In the previous analysis of experiments called out in the RFP, angular acceleration thresholds were combined with the linear accelerations threshold experiments. The techniques involved, however, are sufficiently different to separate these measurements. The experimental determination for a perceptual threshold to rotation has been under way for many years. Dr. Brant Clark, in a very complete review on the thresholds for the perception of angular acceleration in man points out that Darwin started this work in 1801 and that Purkinje systematized the research during the period 1820 and 1825. Dr. Clark's review of the field is quite thorough, and thresholds have been reported between $0.035^{\circ}/sec^2$ and $8.5^{\circ}/sec^2$ (Clark, 1967) with a median of around $1^{\circ}/sec^2$. He attributes this large variation to differences in methods and in definitions of threshold. Stewart and Clark are currently continuing the research on perceptual thresholds for angular acceleration at Ames Research Laboratory using a simulator that is computer driven and programmed to the subject's reaction, thus giving extremely fine control. At present their research is confined to the yaw response or angular accelerations about the man's Z axis. The influence that the otolith might have on the semi-circular canal responses for detection of angular acceleration is difficult to evaluate under 1-g conditions. The centrifuge offers a unique opportunity to compare sensitivities at 0-g with 1-g. Although fine control and freedom from vibration cannot be duplicated in space as it is in the Ames Laboratory, the centrifuge arm can be used with the

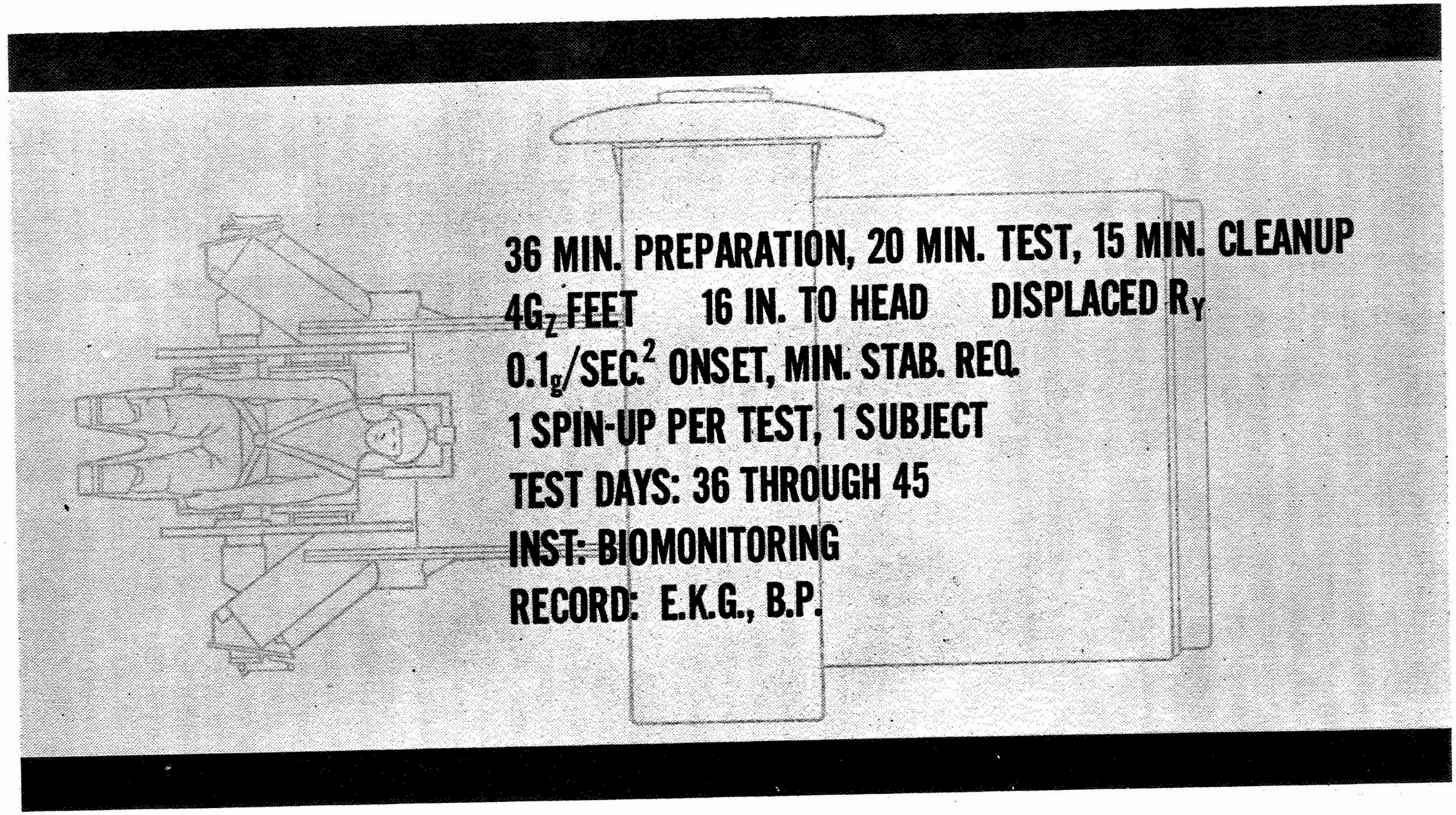


Figure 5. T-010B, Therapeutic.

technique developed by Stewart and Clark. By giving the couch continuous freedom about the centrifuge radial axis so that man can be spun about his Z axis to produce a yaw motion, it is possible to change his rpm slightly and determine if he detects this by means of nystagmography or the oculogyral illusion used by Stewart and Clark. The research at Ames presently uses a 10 second burst of acceleration (or deceleration). The subject indicates a sensation of acceleration to the left or right while looking at an illuminated target in a dark room, and this is fed into the computer which is programmed to give the next stimulus to the subject. If the subject does not detect the stimulus, the computer program automatically increases the stimulus to the point where it is detected. In this way the liminal stimulation is determined. The same approach is proposed for the centrifuge, using an on-board computer.

The Ames Man-Carrying Rotation Device (MCRD) programs the accelerations through a plus or minus (clockwise or counterclockwise) rotation of 10 rpm. This provides acceleration bursts in random form for rather high acceleration levels to accommodate insensitive subjects. The space subjects can be presumed to be either normal or more sensitive and should require no more than a $1.0^o/sec^2$ acceleration for .1 second. With this advantage, the same program of step acceleration in random form should be possible while rotating in only one direction without exceeding 6.0 rpm. This obviates going through 0 rpm during an acceleration and greatly reduces the possible vehicle perturbation and the resulting cross coupling at high rpm's.

In all acceleration studies in the space environment the vehicle stability is very important. Control of the environment should ideally be a magnitude lower than the anticipated threshold being measured. When the centrifuge is spinning about an axis and the vehicle makes an arc about a different axis, a cross coupling is produced that is orthogonal to the two angular motions. The magnitude is the product of the two angular velocities and, therefore, can easily exceed the liminal value. Stated diffferntly, this apparent motion in a different plane can cause the subject to respond when he should not and it decreases the sensitivity of the test. The stability requirements and means of achieving them is covered in Volume I.

The responses to acceleration in null gravity conditions can be compared to the laboratory values to assess the otolith interaction that has been proposed (Mayne, 1945) It would be desirable to obtain intermediate points between 0 and 1-g. Unfortunately, if the space centrifuge is spun to produce a low level of centrifugal force comparable to a fraction of a g with simultaneous spin of the couch around the subject's Z axis, cross coupled accelerations would result about an axis other than the subject's axis of rotation.

Stewart and Clark are planning to measure threshold axes other than the Z and these can also be compared with the 0 g values obtained in the space centrifuge. These determinations can be done with the basic centrifuge rotation drive.

Experimental - Thresholds for acceleration detection will be determined in the X, Y and Z axes. Test days will be 2, 9, 19, 23, 30, 37, and 44th days using two astronauts as subjects. The determinations will be made using subjective response while watching an illuminated target, and the step accelerations will be administered by computer program. The X and Y axes tests will use the normal centrifuge rotation mechanisms, but the centrifuge arm will be locked for the Z axis threshold determinations and the couch will be rotated about its long axis. Accelerations will be negative or positive in 10-second busts of velocity change between 0 and 6 rpm. The head will be positioned at the center of rotation in X and Y tests but need not be centered for the Z test. Figure 6 shows the centrifuge arrangement for the R_Z position.

T-010D - Tolerance To Tilt Simulation. - Background. - The tilt table has been used for many years to assess the reactions that occur in the vascular system in response to exposure to one g. When the subject on the tilt table is changed from a horizontal to a near vertical, it brings about a reactive process that is dependent on many different body systems. Important in these mechanisms are the change in heart rate, blood pressure vasomotor tone and brain perfusion. These changes have been studied by many investigators who used the test in early aviation medicine, such as Graybiel (1941), for pilot examinations and it has assumed a naturally important role in evaluation of space effects on the Mercury and Gemini pilots. Tilt table procedures are somewhat standardized from experiments done to investigate bedrest as a means of simulating weightlessness and inactivity, Fascenelli (1966), Murray et al (1966) and Vogt (1966). Vogt has developed a data retrieval and handling method which allows computer storage and analysis of the subject's reaction to the tilt table test. His procedure is a recording of baseline data on heart rate and blood pressure for five minutes in the horizontal. The subject is then tilted in 35 seconds, to the upright position of 70° from the horizontal, for 20 minutes unless syncope or impending syncope occurs.

Because so much baseline data is available for the tilt table, it is very desirable to have a test on board the vehicle that would be comparable and, therefore, meaningful to monitoring physicians.

To accomplish this, the test in space must be done at the equivalent of one-g acceleration and, in addition, have the same hydrostatic gradients imposed during horizontal and tilt as is evoked by the 70° tilt on earth. Three alternatives were investigated to accomplish this with use of the centrifuge:

a. Positioning the manalong the radius and then increasing the rpm will cause an increased hydrostatic gradient. However, without manipulating his position, the earth equivalent for either horizontal or tilt cannot be achieved. The zero-g situation is in essence the same as horizontal for the earth referenced head to foot hydrostatic gradient, but the chest to back gradients are not equivalent. When spun up to one-g at the heart, there is a much higher gradient from head to foot than under earth conditions. This method was therefore discarded.

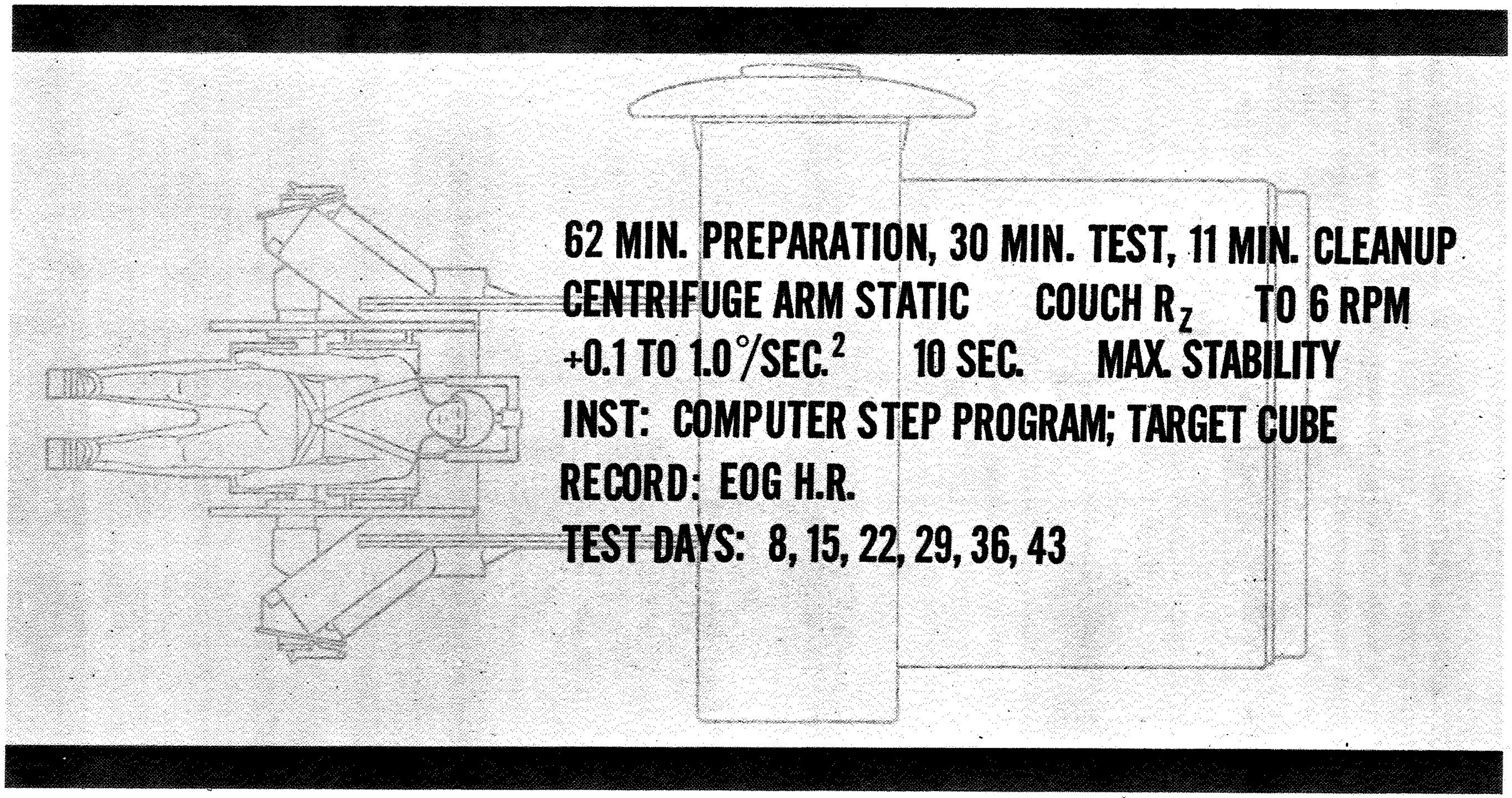


Figure 6. T-010C, R_z Threshold.

b. The man could be positioned parallel to the spin axis and then spun to a 1-g equivalent which would duplicate the horizontal condition on the tilt table. Tilting, however, would then be out of the plane of spin and could evoke cross coupling and coriolis accelerations which also affect the sympathetic nervous system. It would be difficult to separate symptoms due to postural change from vestibular symptoms. The method also requires an increased spin envelope for the centrifuge housing.

c. The most practical method is that of arranging the couch on a circumference of the circle so a nearly uniform level of g is imposed on the subject. The radius and rpm are then chosen so that as the couch is tilted with the head remaining at a constant radius, a gradient from head to toe is produced that is comparable to a 70° tilt. Appendix A shows the mathematical derivation of the arrangement. An important experiment to be performed in the ground-based simulator will be the correlation of tilt table response with that derived from the facsimile on the centrifuge.

Vogt has developed an analytical method for assessing the heart rate and blood pressure during tilt that seems very appropriate for space use. The analysis examines the following:

a. Average heart rate (HR pre-tilt).

b. Maximum HR during tilt.

c. Minimum HR after tilt.

d. Change in HR with tilt.

e. Average HR pre-tilt minus average HR post-tilt.

f. Time of maximum HR.

g. Time to 80% maximum HR.

h. Time to plateau of HR.

i. Slope to 80% HR (beats/min./min.).

j. Slope to plateau (beats/min./min.).

k. Minimum pulse pressure (PP) during tilt.

l. Average PP pre-tilt minus minimum PP during tilt.

m. Fractional decrease in pulse pressure.

n. Slope of diastolic blood pressure (BP).

o. Slope of systolic BP.

p. Slope of PP.

q. Time at break in HR curves.

r. HR at break.

s. Slope of first and second HR data line.

t. Time at break of PP.

u. BP at break.

v. Slope at first and second line of pulse pressure.

All of the above is derived from the two measurements, heart rate and blood pressure (systolic and diastolic), and each has been used to interpret the physiological state of the subject. Depending on computer availability, either the above data can be reduced and then transmitted or each test can be recorded and then transmitted for ground analysis. The on-board monitor will require real time display of heart rate and blood pressure during this experiment to terminate the tilt before syncope occurs.

Experimental. - Exposure to tilt table tests has been used as a measure of debilitation after exposure to prolonged water immersion and to weightlessness in the Gemini program. Periodic exposure to a similar test while in space flights of longer duration is practical with the SRC capability. The subject is positioned on a saddle-type restraint attached to the couch and is stretched along an arc of constant radius. The centrifuge is brought up to proper speed. The subject is then tilted outboard from the center of spin. The radius of rotation and the position of the couch should develop a pressure distribution in the blood system as close as possible to the pressure gradient obtained when tilted in earth gravity. This gradient can be duplicated by maintaining the head at 1.0 g before and after tilt (Reference Figure 7).

Tilt Table Configuration. -

a. 1-g at head before and after tilt.

b. Head remains at a constant 40 inch radius-before, during and after tilt.

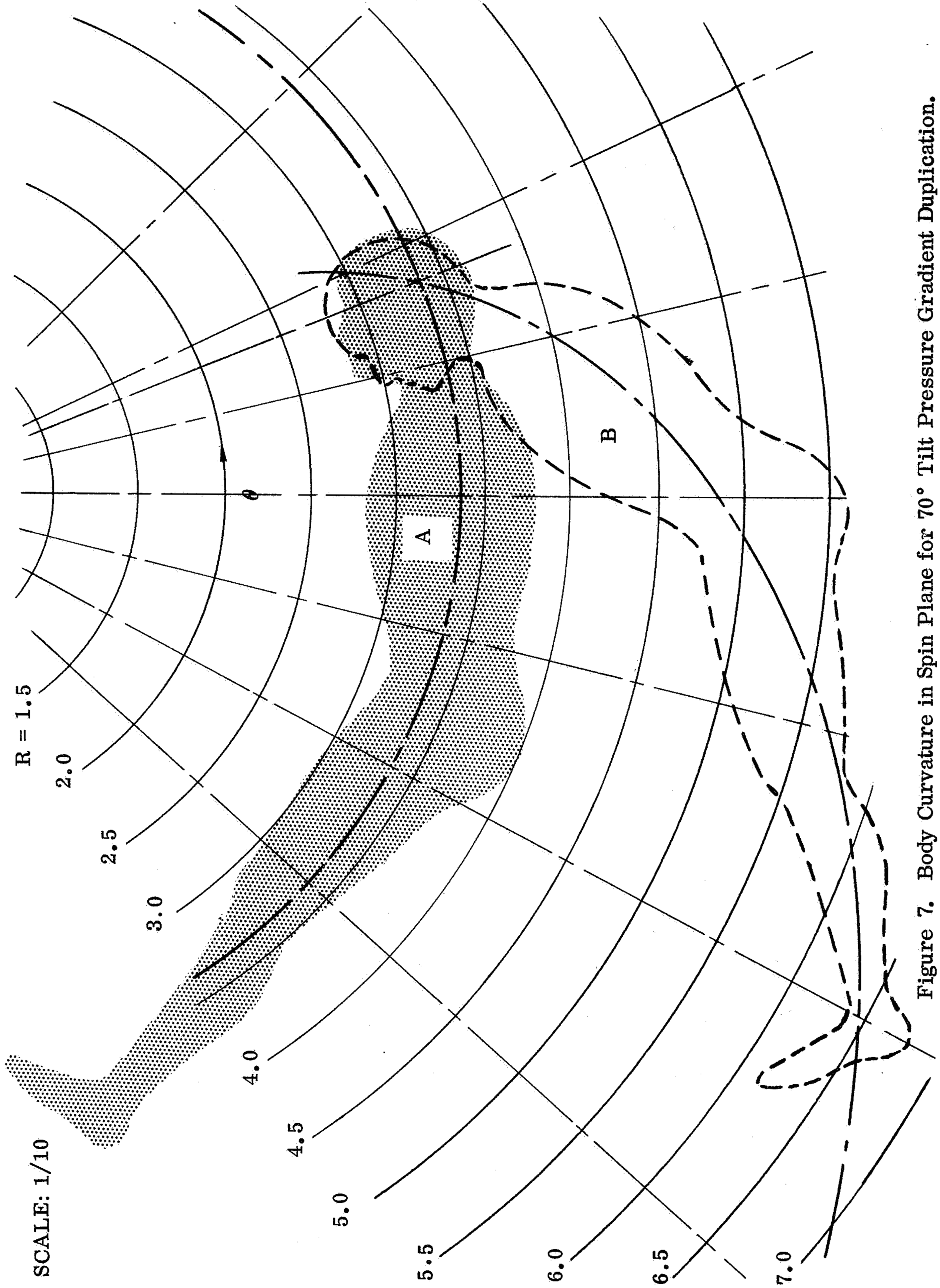


Figure 7. Body Curvature in Spin Plane for 70° Tilt Pressure Gradient Duplication.

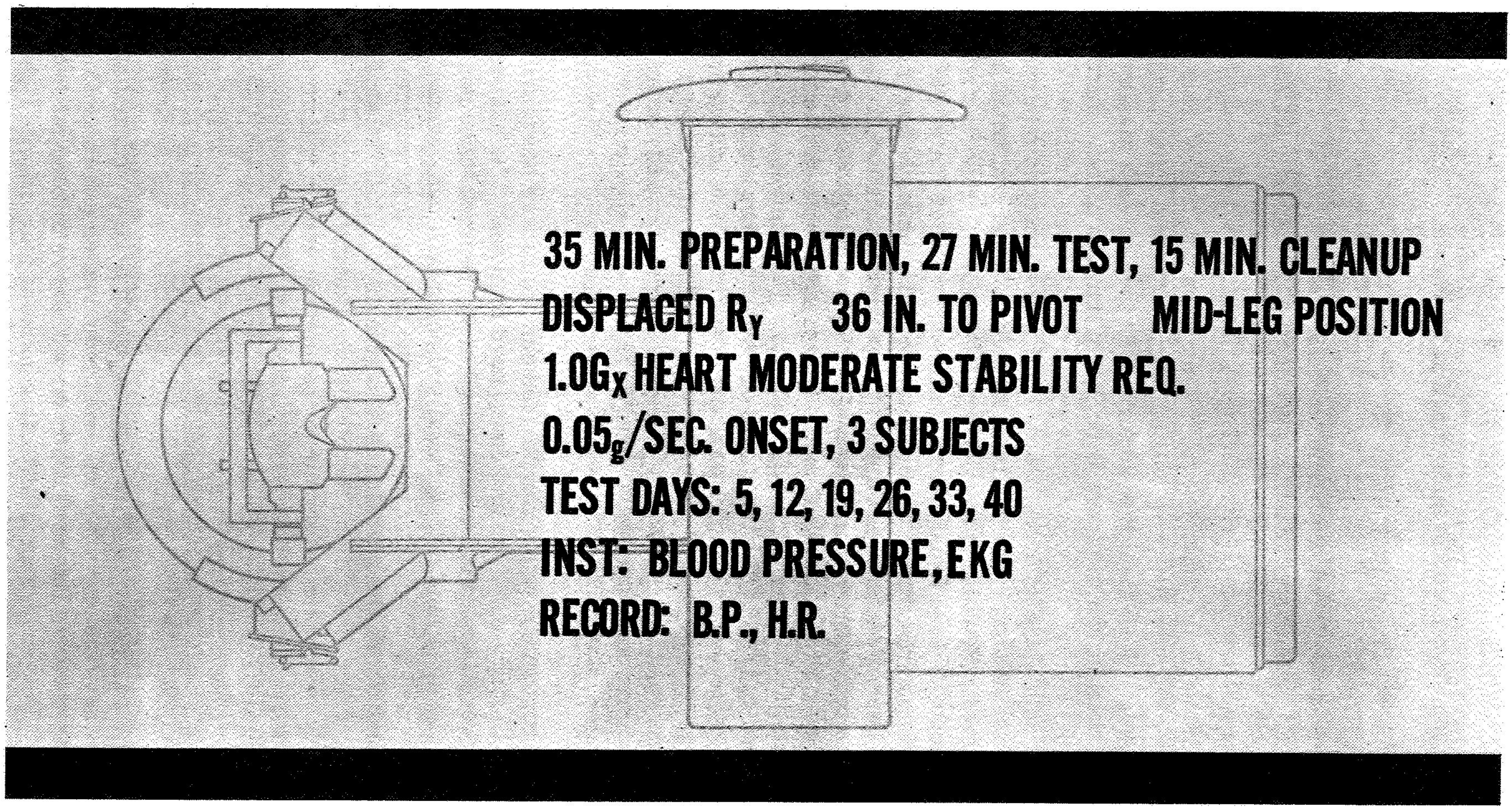


Figure 8. T-010D, Tilt Table.

c. Centrifuge speed is maintained at 29.6 rpm.

d. Time to accomplish tilt is 35 seconds.

The experiment shall be performed on the 5, 12, 19, 26, 33, and 40th days. Two astronauts shall be subjects of this experiment. The experiment will involve 12 runs during the 45 day period.

T-010E - Cross Coupled Semicircular Canals Stimulation. - Background. - In an artificial-g space station, the crew will be aligned with the centrifugal force and be in the plane of spin. Side-to-side head turns will then cause a maximum amount of cross coupling because the motion will be 90° to the spin plane. Earth simulation of such stations has been typically performed with the subject displaced nearly at right angles to the spin plane so side-to-side head turns produced minimum cross coupling. This error in simulation has been studied by Stone and Letko at Langley Research Center and by Newsom et al at General Dynamics. Disorientation from head turning and nodding were found to be significantly greater out of the plane of spin than in the plane of spin by criteria of performance and voluntary rate of head turn. From the General Dynamics studies it appears that the degradation in performance increases at a ratio of 1.6 from comparison of performance following 0° and 90° interplanar angle head turns. It was found that disorientation rather than nystagmus was responsible for the degradation in performance. Performance decreased as fixation time of the eyes on the target increased or as interplanar angle increased. The amount of interaction between semicircular canals and otolith is not known, and in space it will be possible to repeat the studies cited utilizing subject alignment similar to the space station orientation. The cross-coupled acceleration is nearly independent of radius and results obtained on the centrifuge in space should be quite appropriate for use in design of any future artificial g system.

A standard performance test can be used and the rate of head turn recorded in both the Z (side to side) and Y (up and down) head motions. The subjects can be positioned so their gaze is tangential, axial, and at 45° between those positions. Data to be recorded will be head turn rate, vertical and horizontal oculograms, performance, latency response, and eye fixation time. The tests will be repeated at increasing rpm's to the point where the stimulus is disagreeable. When the study is performed with the head at center of rotation, the otolith should have a zero g stimulus; however, when the study is repeated at maximum radius, the otolith will be stimulated at increased rate proportional to the square of the rpm. From this information, the interaction between otolith and semicircular canals can be assessed. Suggestions of such interact on have been made by Guedry and Montigue (1961), Lansberg (1965), and by Mayne (1965).

Experimental procedures will require the couch to be positioned at two radii; one with the head at zero and the other at a maximum radius (which is 45 inches to the head with the feet elevated). The head restraint will serve to keep the head motions in a correct plane. The performance test can consist of four colored lights, each with a corresponding button (flexible button pattern). A 70° head turn is initiated on

signal and the subject pushes the buttons in his lap to change as many lights as he can in a timed period. The lights are collimated to 1^{o} angle so vertical and horizontal oculograms can be made and also integrated into a vectoroculograph to derive fixation times. Head turn rates will also be recorded and can be analyzed in the manner used by Stone and Letko. The data from these tests can be recorded and transmitted for ground analysis following each test.

Experimental. - Experiments shall be made with one subject on the 3, 10, 17, 24, 31, and 38th day and another on the 4, 11, 18, 25, 32, and 39th day. The experiment shall be performed at two radii; one with the ear at the center of rotation and the other at maximum radius. The subjects shall be oriented facing tangential, 45^{o}, and normal to the plane of rotation. Specific tasks requiring head motions and hand dexterity will be performed and the head position, head rates of motion, and time of performance will be measured. These experiments shall be run for one to two hours at each radius. Two rates of rotation, 4 rpm and 10 rpm, will be used. Orientation will be as shown by Figure 9.

T-010F - Threshold Levels Of Sensitivity To Linear Acceleration. - Background. - The purpose is to measure the g sensitivity in space to determine if prolonged zero g exposure alters the sensitivity of the otolith organ to which linear acceleration detection is usually attributed. In the space situation, the perception of G_Z+ at levels below one g must be determined by changing either the rpm or radius at rates below those which cause semicircular canal stimulation.

The standard means for investigating otolith activity has been established at the Naval School of Aviation Medicine using both oculogravic illusions and counter-rolling. The counter-rolling technique is quite applicable to space research; however, the oculogravic illusion as usually used on the centrifuge is more difficult to duplicate. The oculogravic illusion, in usual context, is the sensation of the body being aligned with the resultant from two linear accelerations. On earth this is usually one g plus a vector, either an acceleration resulting from a rapid change in velocity (angular or linear) or a centrifugal force. In space, where one g is not present, the duplication of this phenomenum is more complex. Placing the subject's Z axis parallel to the spin axis and rotating him about the eccentric axis in space would produce only a lateral force and the subject could not be anticipated to sense a tilt but rather a simple acceleration in the direction of the centrifugal force. If one acceleration is produced by a centrifugal force through rotation around the centrifuge axis and an attempt is made to produce another linear vector by rotation in a different plane, a gyroscopic or angular acceleration is produced which is not comparable to the earth situation. In such a situation the semicircular canals could be expected to predominate in stimulus reaction over the otolith.

An alternative to this approach would be to produce a basic acceleration by means of a rocket burn. This would provide a nearly linear acceleration to which could be added the centrifugal acceleration of the centrifuge. This is a possibility but a rather complicated procedure for any first attempts at the use of a centrifuge device in space.

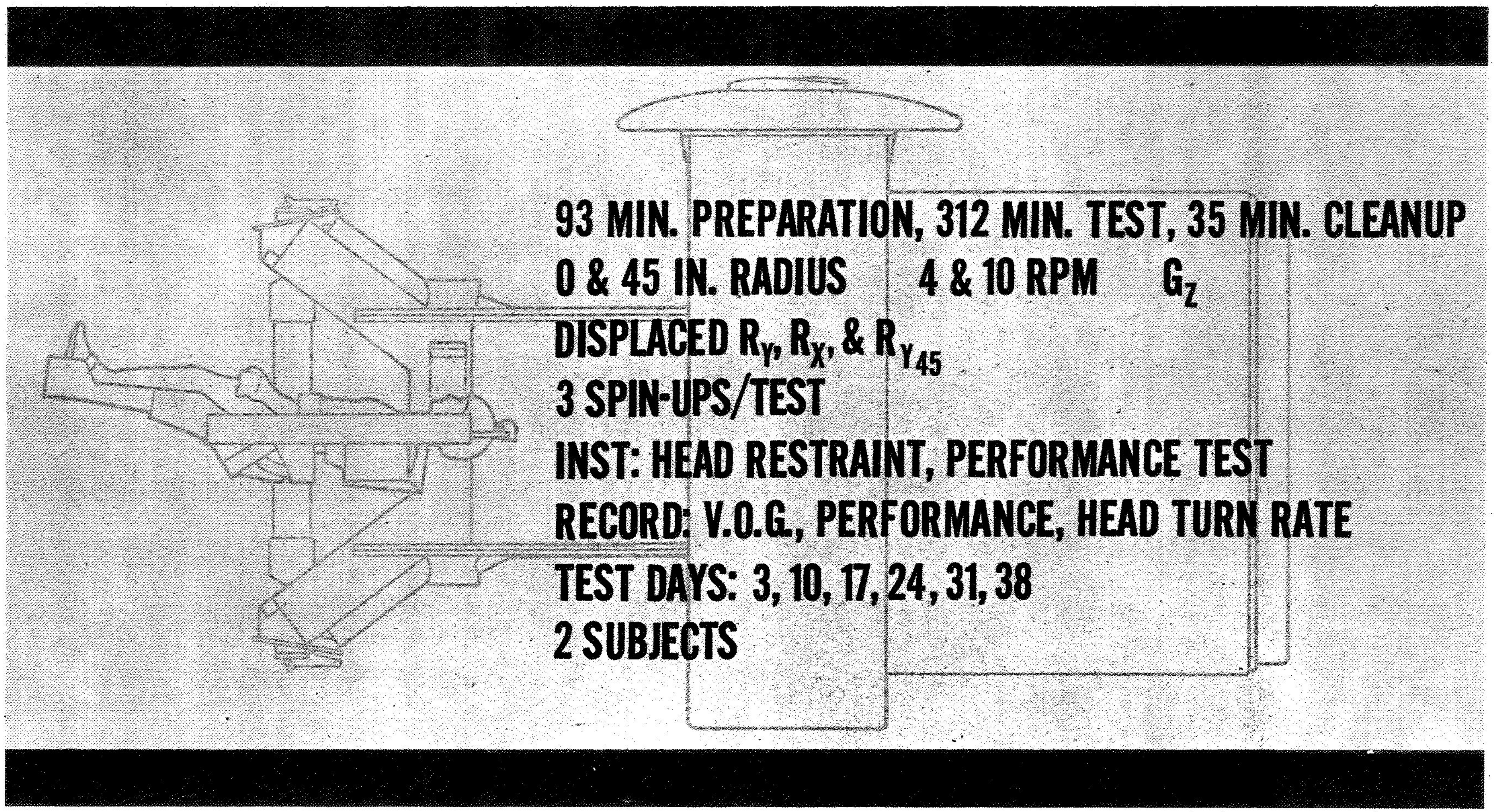


Figure 9. T-010E, Coupled Angular Velocities.

The zero-g environment can be used to investigate mechanisms, sensitivities and thresholds of angular deflections of the otolith by the use of two classical techniques not dependent upon vector addition. These are the counter-rolling techniques developed by Miller and the sensitivity to tilt or the A and the E phenomena. Another tool available is the elevator illusion but it has not been nearly so well documented.

The normal function of the otolith, or at least the most used function, is to determine the alignment of the body or head with the vertical. Measurements have been made, however, on the sensitivity of the organ to its role as a linear accelerometer in the vertical. Graybiel and Patterson (1955) deduced a sensitivity of the otolith to .00034 g changes by the oculogravic illusion. It is more likely, however, that what was being determined was the sensitivity to the .02 g lateral vector that was imposed by centrifugation rather than the extremely small increase in the resultant vector.

In a later study by Niven Whiteside and Graybiel (1963) the motion of a visual target was investigated in a high speed elevator and in a drop tower. The image was referred to as the elevator illusion. A real target had an apparent downward movement when the g was greater than one (elevator going up) and an apparent upward movement when the g was less than 1. In a labyrinth-defective subject neither illusion nor eye movement was observed and it was concluded that the reflex was an otolith stimulus response. This elevator illusion was later observed in parabolic flights by Roman, Warren and Graybiel (1966).

The otolith sensitivity to various g levels can be assessed on the centrifuge by spinning the subject along the radius so a comparison of various g levels can be made (when presented in random order). The elevator illusion, like most subjective measures, is difficult to quantify as verbalization of the sensation will be variable between subjects. The effect, however, should be measurable by adjusting a line on the perceived horizon which is the "egocentric visual location" technique used by Miller and Graybiel, and also by the measurement of the eye motion using the vector oculograph technique used by Newsom et al. The measurements can be made simultaneously.

Investigations of man's ability to detect his orientation in roll, with respect to the gravity vector, has been under investigation for many years. Error in this perception has been described by the A (Aubert phenomenon) and E (phenomenon described by Muller). Diefenback (1961) summarizes much of the work leading up to his experiments of immersed subjects in which he described the gross errors made by all subjects in their ability to indicate the vertical (in pitch). Below 80° off the vertical (in pitch). Below 80° off the vertical the error was less than 30° the error increased rapidly in three of the four subjects to between 80° and 100° . Miller et al (1965) investigated tilts of dry subjects in roll and indicated the error in terms of the EVL (egocentric visual localization) as a function up to ±90° from the vertical. The E effect started 20° off the vertical and errors increased from 4° to as much as 25° at 40° off the vertical. The A phenomenon became apparent beyond 80° off the vertical.

Figure 12 is from Miller et al with the letters E and A added. In a zero g environment the vertical does not exist and, if the curves representing the A and E responses are dependent upon g reinforcement, then the shape of the curve when exposed to a centrifuge force may change with prolonged exposure to weightlessness.

When the inertial resultant is deviated from a vertically oriented subject, it has the same effect as if the subject were tilted from the vertical. The otolith and the proprioceptors align with the resultant force and the subject has the illusion of tilting when he is without visual reference. This illusion is referred to by Graybiel (1952) as the Oculogravic Illusion (OGI). As discussed previously, the OGI is not easy to produce in space and the measurements of tilt will not be of the illusion type but rather the A and E sensitivity to being tilted off the inertial resultant in terms of the error in judging that deviation at different g levels.

When the subject is rotated around an X axis through the head, the response of the eyes is not a vertical or horizontal displacement but a rotation around the pupil. This reflex motion is called counter-rolling by Miller et al and is used to assess the otolith activity in the same manner as the EVL. Miller has photographed the eye rotation and correlated it with the degree of body tilt. Miller, Graybiel, and Kellogg (1966) measured the counter-rolling of otolith-defective subjects and compared these to normal subjects at 0, 1/2, and 1 g. The hypo g environment was accomplished using parabolic flight maneuvers. Figure 11 is taken from that report and the measurements at 0^{o}, $\pm 25^{o}$ and $\pm 50^{o}$ indicate significant changes in response. The photographic technique must be such that camera and skull have a fixed and constant relation. The counter-rolling of 3^{o} and 6^{o} at 25^{o} and 45^{o} tilt are large enough, however, to be practical for a space study. The equipment used can be considerably lighter than the laboratory version used in the cited study as that equipment is accurate to 2 minutes of arc for detection of very small angles of tilt.

The vector oculograph is not sensitive to counter-rolling because there is no vertical or horizontal eye movement, but it can be used for detection of eye responses in pitch or variable g level.

Experimental. - The Space Research Centrifuge will make an excellent test facility for examination of otolith response at variable g levels. The couch position to be used is with feet elevated to give maximum radius. At this position the radius to the head is 45 inches; rotation rates are approximately 33 rpm for 1 g, 22.5 rpm for 1/2 g, and 16 rpm for 1/4 g. All subjects can be tested for zero g baseline soon after orbiting. One member can then be tested again at 7, 25 and 56 days*, another at 14, 36 and 72 days*, and the third at 21, 45 and 90 days*. (*Omitted in 45 day mission). This will provide information on the zero-g response of a normal otolith and determine the manner, if any, in which that response changes.

Part 1: The subject is measured for subjective, EVLH and VOG response to 1/4, 1/2 and 1-g at pitch angles (Y axis) of 0^{o}, 15^{o}, 30^{o} and 45^{o}. The couch is positioned so the subject faces tangentially for EVLH reactions.

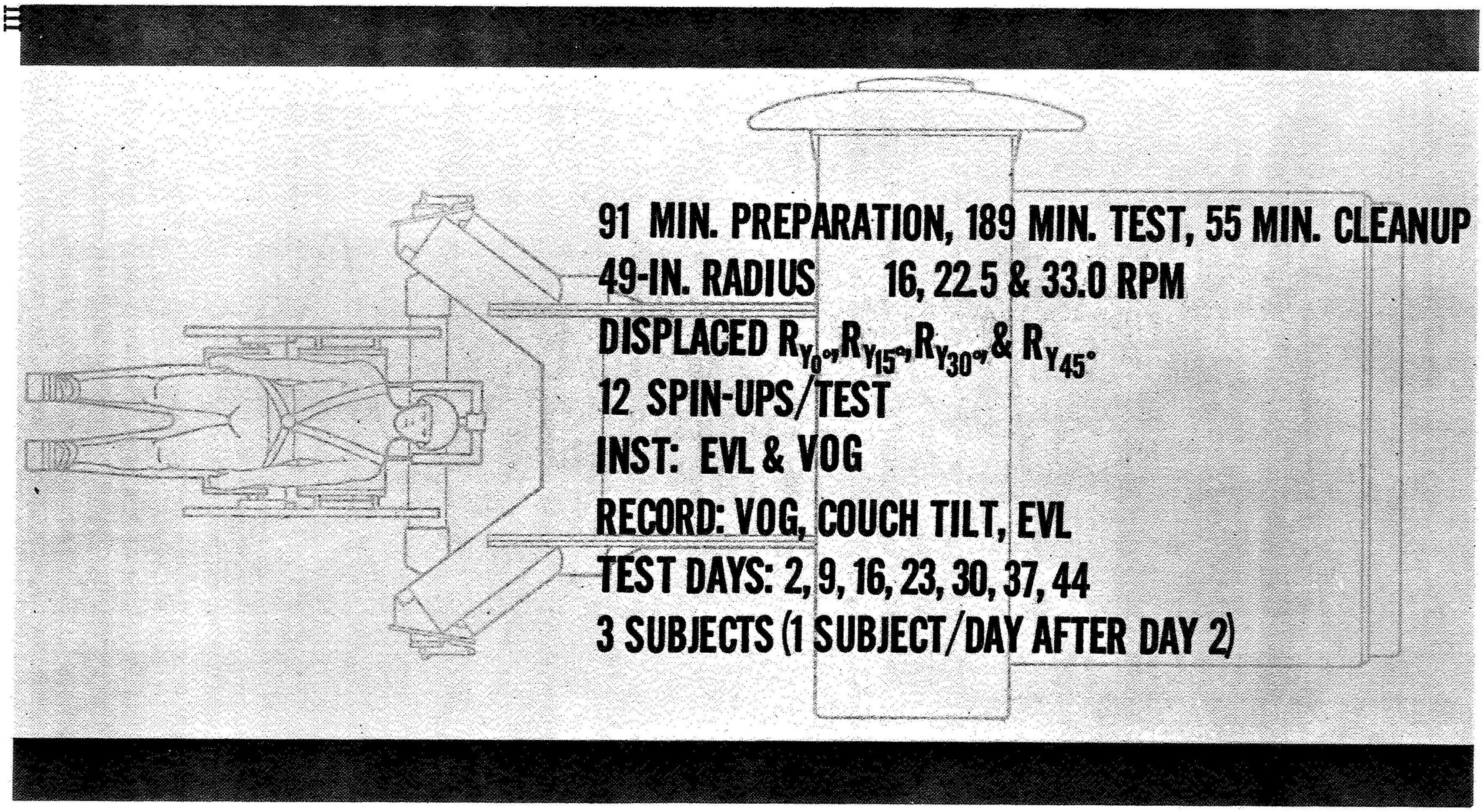


Figure 10. T-010F, g-Sensitivity, Part 1.

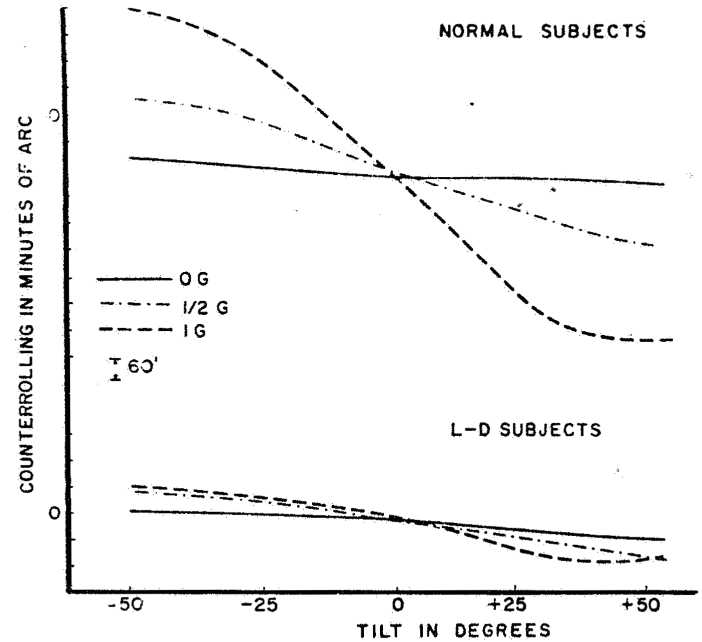


Figure 11. Counterrolling as a Function of Magnitude of Gravitational Force (Zero G, 1/2 G, 1 G) and Body Position with Respect to Direction of Force in Normal and Labyrinthine-defective Subjects. (From Miller et al, 1966.)

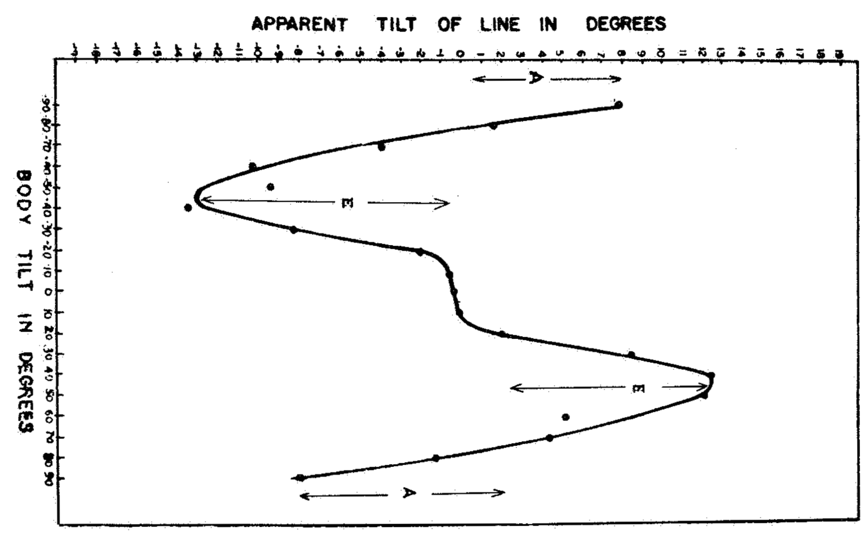


Figure 12. Mean Deviation of the Apparent Horizontal Position of a Line Target from its Physical Horizontal Position as a Function of Body Tilt (From Miller et al, 1965).

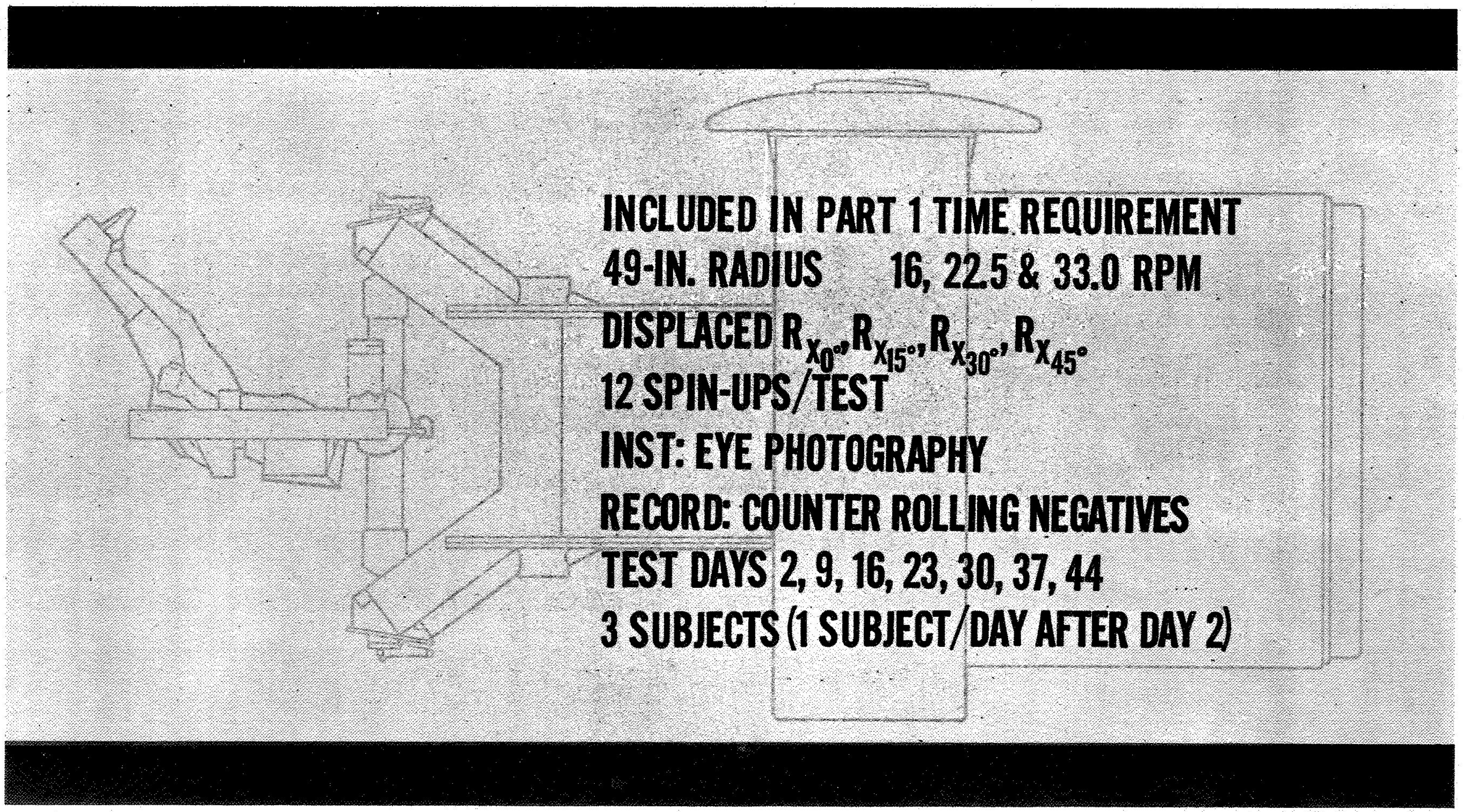


Figure 13. T-010F, g-Sensitivity, Part 2.

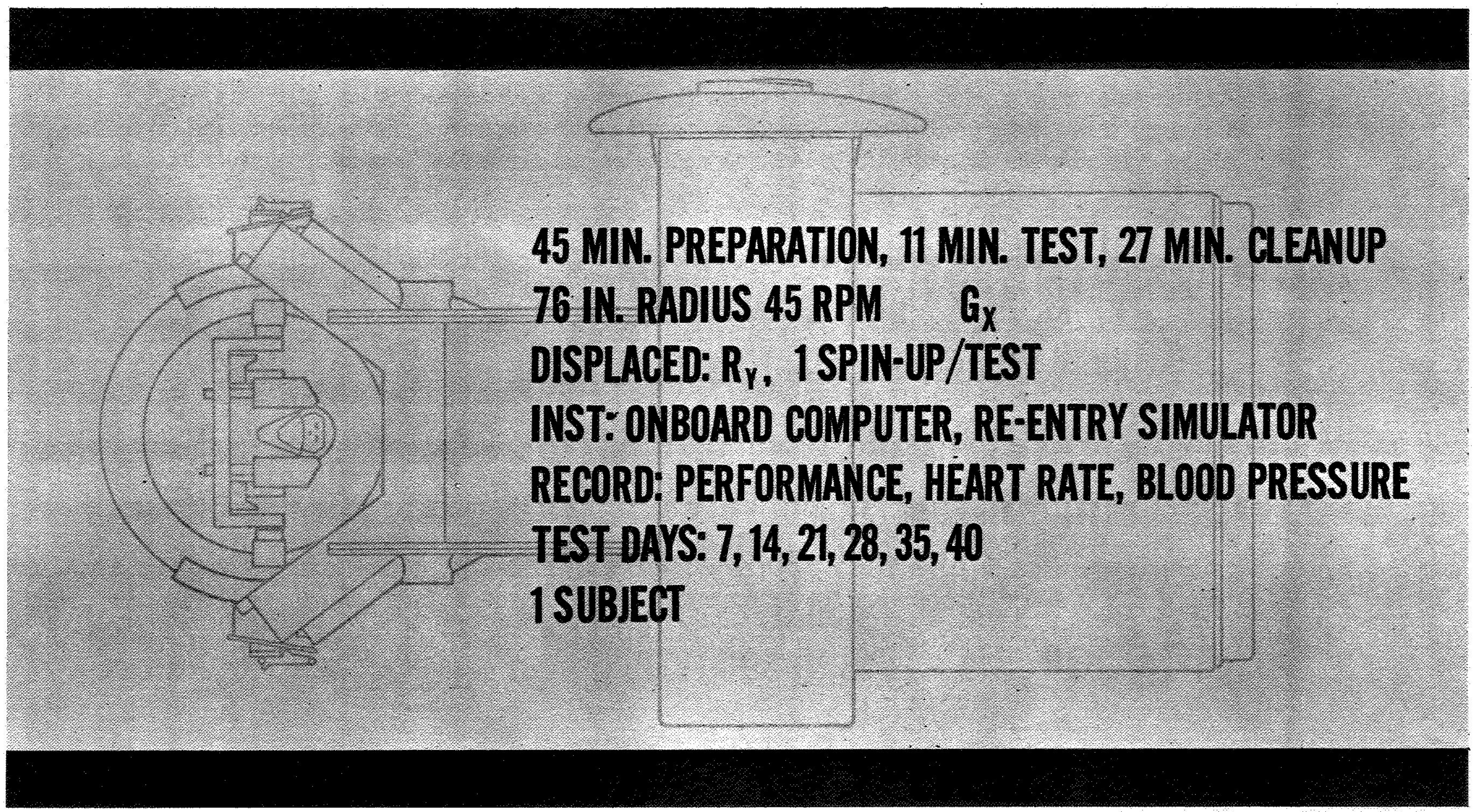


Figure 14. T-010G, Re-entry Simulation.

Part 2: With the couch positioned so subject faces axially, his subjective A and E and counter-rolling response to 1/4, 1/2 and 1-g is measured at roll angles (X axis) of 0^o, 15^o, and 45^o.

T-010G Re-Entry Simulation. - Background. - Some consternation has been shown from parts of the space medicine community that prolonged missions at null gravity would decrease the astronaut's ability to fly re-entry because of lack of practice and loss of g tolerance. To circumvent this it has been proposed that prior to re-entry the crew be exposed to the re-entry profile on a centrifuge and perform the re-entry control task. Ideally the flight controls would be included on the couch and the subject's reactions would invoke the g changes resulting from any of his errors. This would be an extremely sophisticated simulator for orbital use and could cause injury to the subject were the high acceleration levels oriented through the Z axis. A much simpler approach is to use the simulator only as a physiological challenge and practice a re-entry type routine during the acceleration. For this the centrifuge rpm level can be programmed in a simple manner. As the resultant g levels will not all be through the ideal transverse (G_X) axis, it is also necessary to program the couch orientation so it moves off the nominal position to re-align the g vector. The couch would be at maximum radius with the subject's Z axis 78^o off the radius (transverse g tolerance is increased when back is raised 12^o to decrease pulmonary distress). Proficiency in flight control during the high g profile can be determined with a performance test that reflects the control problem. Such a performance test would be much simpler to control and evaluate. The NASA developed Perceptual Motor Test Console has several test routines that would be appropriate (Parker et al, 1965) and the console could be miniaturized for this purpose.

Experimental. - The experimental plan is to expose one of the three crew members on days 7, 14, 21, 28, 35 and 40 to this simulation. There is, however, a conflict in this experiment with the therapeutic conditioning procedure and they accomplish the precise opposite physiological effects.

The exposure of transverse g will cause an increased central blood volume, stretch the left atrial wall and inhibit antidiuretic hormone via the vagus and reticular formation (Gauer and Henry, 1963, Gauer et al, 1961). The degree to which these exposures would further decrease the circulating volume of an astronaut that is already hypovolemic by earth standards is not known. But, by the results of Piemme et al (1966), it is certainly a factor to be considered carefully because it may lower the physiological tolerance rather than improve the re-entry capability. This would be particularly true if an off-nominal entry path were experienced. The experiment also prevents the use of that subject for testing the therapeutic value of G_Z exposures or for using him as a control to that experiment.

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COUCH DESIGN PRECEPTS

Summary of Requirements

Figure 15, shows a complete list of experiments and relations with couch positions, accelerations, type of restraints, degrees of freedom and experimental instrumentation required for the success of the mission.

Restraint System

Figure 16 shows the couch design concept to which any restraint system should complement. Some assumptions must be considered for the selection of the most reliable restraint system:

a. Forces that may jeopardize the subjects by imposing stresses beyond human tolerance are not expected during the mission.

b. The restraint system should allow manipulation of the experiment instruments within the subject's normal reach envelope.

c. It is important to include within the concept a minimum number of motions to free the subject from any position he may be in after abort by means of a single release or simple manual motions.

d. Provisions must be taken, to permit a single man operation of motions concerning couch position, adjustment, donning restraint latching, etc.

e. Initial subject accommodation on the couch during weightless condition presents the folliwng problems:

   1. Pressure points will not be noticed before the g load is applied.

   2. Eye leveling with respect to instruments should be compensated to a cushioned seat panel or saddle due to compression of the material while rotating.

   3. For the same reason, couch pivot points should be adaptable to different body motions.

Tailoring the couch to the individual astronauts may be a useful approach in providing full or partial body support.

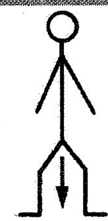
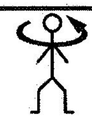
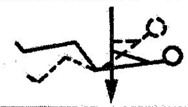
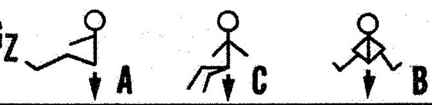
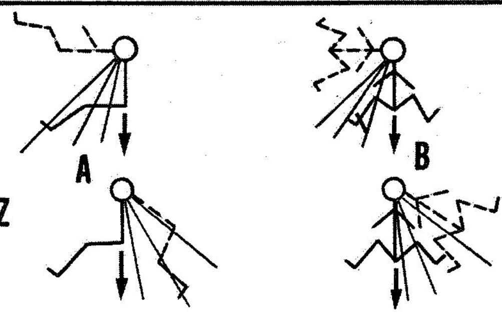
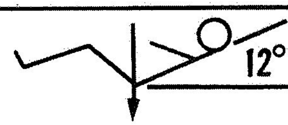
EXPERIMENT	BODY COORDINATE EFFECT	ORIENTATION	ACCELERATION
GRAYOUT	$+G_Z$ 	RADIAL FACING NORMAL	UP TO 6G AT FEET-INITIAL ONSET 0.1 G/SEC.
THERAPEUTIC	$+G_Z$	SAME	G ONSET 0.1 G/SEC.
ANGULAR ACCELERATION		SAME FOR INITIAL & FINAL POSITION	10-SEC. BURSTS OF 0.03-1.0G
TILT TABLE	$+G_X$ 	I-PERIMETRIC FACING CTR. II-ALONG DYNAMIC CURVE	0.05 G ONSET
SEMICIRCULAR CANAL STIMULATION	$+G_Z$ 	A-RADIAL FACING TAN. B-RADIAL FACING NORM C-RADIAL FACING 45°	0 TO 1G AT EARS
SENSITIVITY TO LINEAR ACCELERATION	$+G_Z$ 	RADIAL FACING TAN. 0°, 15°, 30°, 45° RADIAL FACING NORMAL 0°, 15°, 30°, 45°	0.2G,-0.5G & 1G AT EARS
RE-ENTRY SIMULATION	$+G_X$ 	PERIMETRIC - 12° FACING CENTER	0 – 9G

Figure 15. Experiment Summary

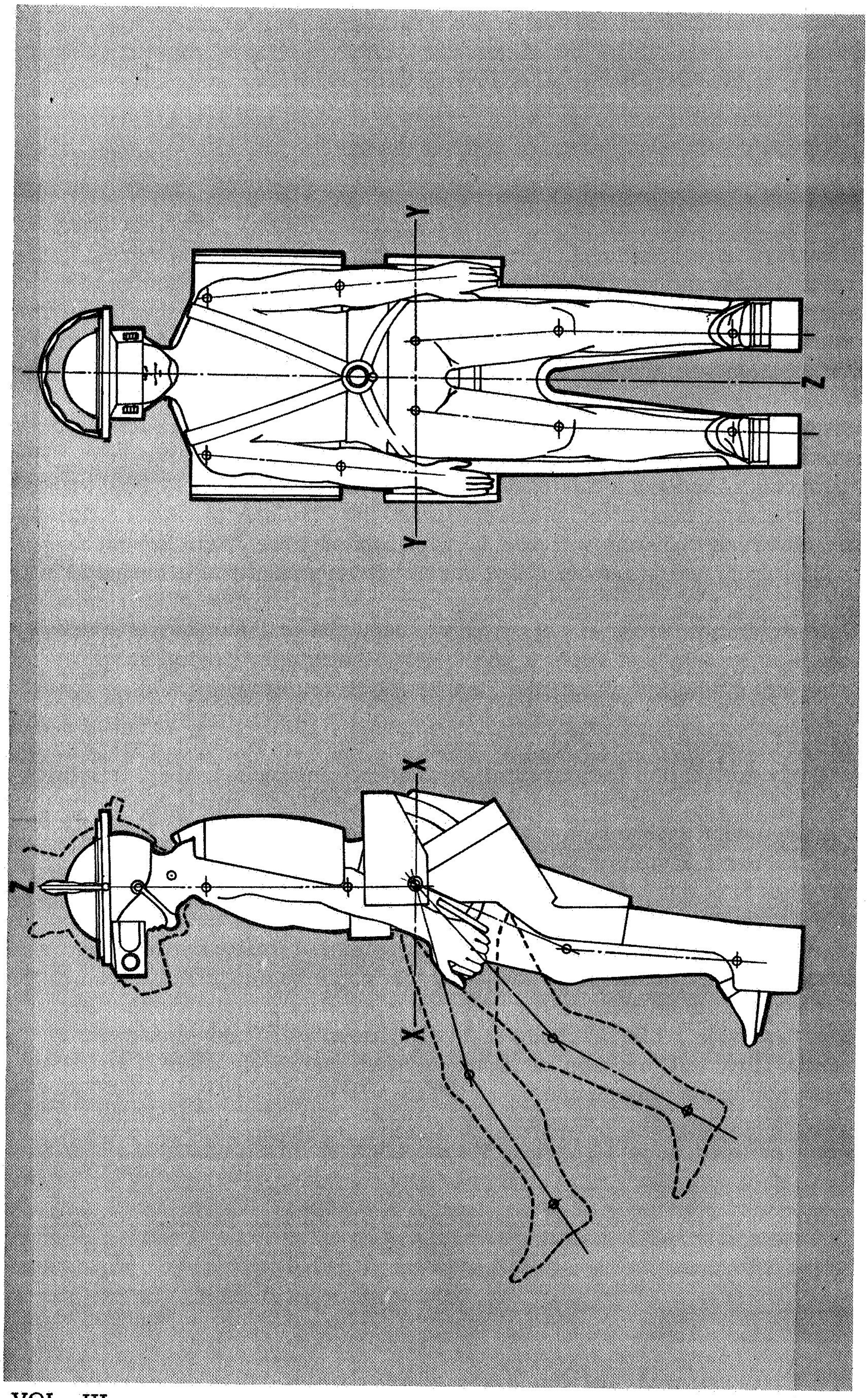


Figure 16. Couch Concept and Positioning Requirements.

BIO-INSTRUMENTATION REQUIREMENTS

Apparatus incorporated because of experimental or biomonitoring requirement must be fixed in position by means of inserts and clamps. This apparatus consists of that utilized in studies described in the open literature. Table 1 lists some representative centrifuge requirements imposed by the experiments. Instruments, required parameters, and centrifuge and subject controls and drives are listed for the eight proposed centrifuge uses. Mass and volume constraints require test sharing. This is an area where trade-offs must be made during the final experiment design to achieve an acceptable arrangement.

NASA is currently developing the Integrated Medical-Biological Laboratory Measuring System (IMBLMS) under contract to Lockheed and General Electric. The goal of the program is to have a flexible measuring system available by 1970 that will handle most of the crew measuring requirements of the Apollo Application Program. It is assumed that such a system will also be applicable for the Space Research Centrifuge. The proprietory nature of that system development has prevented its incorporation into the SRC feasibility study and the information available from a previous NASA contracted study at Lockheed was used. It is assumed that much of the same design philosophy will apply to the IMBLMS study as was used in the NASw-1071 contract by the LMSC entitled "Biological Measurement of Man in Space."

Known Apollo Application Instrumentation Concepts Pertinent to the Centrifuge*

The instrumentation for biomonitoring the subjects on the centrifuge are assumed to be the basic system developed for the Apollo Application Program. The design of that system is not yet verified, but can be expected to be close to that proposed by the contractors currently studying the requirements. The basic portion of interest is that which monitors the cardiovascular system. Presently this system described in the AAP study ends in an umbilical that could be plugged into the centrifuge couch for conduction by capacitor coupler or telemetered to the monitor from a transmitter on the couch. The proposed telemetry has considerable advantage in fidelity and reliability, but would be an additional item for development if an existing transmitter can not be suitably adapted.

*Pertinent text was taken in part or whole from a Lockheed preliminary AAP Study Report.

Table 1. Preliminary Experiment Requirements

DESIGN REQUIREMENTS *FROM RADIUS **RELATIVE TO SPIN PLANE	GRAYOUT	g THRESHOLD COUNTER ROLL & OGI	CROSS COUPLING	SEMI-CIRCULAR CANAL	TILT TABLE	MASS MEASURE	RE-ENTRY SIMULATION	THERAPUTIC USE
Couch								
Axis drive*	Locked	Locked/Yn	Z	Z	X		X	Locked
Subject, Z axis*	0^o	0, $90/15^o$, 30^o, 45^o	0^o	0^o	0^o		78^o	0^o.
Rate of drive	--	--	$.1^o$ sec.	$.1^o$ sec.	$.1^o$ sec.		--	--
Plane of motion**	0^o	0^o	0^o	0^o	0^o		0^o	--
Palet Configuration	Couch	Couch	Couch	Bed	Bed		Couch	Bed
Subject X axis at start**	0^o	90^o	90^o, 45^o, 0^o	R_z	900		90^o	0^o
Subject acceleration	G_z	G_x & G_x	G_z				G_x	G_z
Head location (radius)		4.5 ft.	0 & 4.5'	0'	5' & 2'		6'	2-1/2'
Centrifuge								
g requirement	0 to 6	0 to 1 head	.15	--	1		76 peak	2 ft.
g onset rate (g/sec.)	.5	.01	.5	.1	.01		.2	.25
Spin duration/trial	1 min.	5 min.	2 hr./rpm	--	20 min.		14 min.	30 min.
Radius	Maximum	4.5	0 + 4.5'	0'	8'		6'	8'
Required Control	.10	.003 g	.01 rpm	.01 g	.01 g		Programmer	.01 rpm
rpm	0 to 60	0 to 30	4 + 10	locked	27		60	27
Computer with g limit		--	--	Step Program	--		Subj. Control	--
Experiment Instrumentation								
Std. Bio-monitoring, EEG etc., TV	Req.	Req.	Req.	Req.	Req.		Req.	Req.
Plethysmograph	Leg	--	--	--	Leg		Leg	Leg
Perimeter lights (control intensity)	23 & 80^o	--	--	--	--		--	--
EVL & NVDI	--	for 15^o, 30^o, 45^o	--	--	--		--	--
Counter Rolling Camera	--	Rigid Mount	Possible	--	--		--	--
V&H Nystamogram	--	VOG	VOG	--	--		--	--
Performance Tester	--	--	Rater	--	--		--	--
Head turn restraint	--	Locked	With turn Indicator	Locked	--		--	Locked
Accelerometer	Heart	Head	Head	--	Feet		Chest	Feet
Schedule								
No. Trials (total)	12	14	12		12		6	40
Days of flight	7, 14, 21, 28 35, 42	2, 9, 16, 23 30, 37, 44	3, 10, 17 24, 31, 38, 4, 11, 18 25, 32, 39	3, 4, 10, 11, 16 17, 18, 24, 25, 31, 32, 38, 39	5, 12 19, 26, 33, 40		7, 14, 21 28, 35, 42	34 to
No. Subjects	2	2	2	3	2		1	1

Table 2. Equipment Characteristics

EQUIPMENT TITLE	WEIGHT (LB)	POWER (WATT)	VOLUME (CU. FT.) STORED	VOLUME (CU. FT.) OPERATE	PRECISION OF MEASURE.	DATA MANAGEMENT AMT. DATA TO BE RECORDED (per meas)	DATA MANAGEMENT FORM OF DATA TO BE RECORDED	DATA MANAGEMENT AUTO OR MANUAL RECORD	EQUIP. LOCATION STORED	EQUIP. LOCATION OPERATE	PRESS. REQ'D
Mass Measurement Device	22.00	1.0	6	36	±0.5 lb	24 bits	Analog	Auto	LEM	LEM	No
Electro Oculograph	0.30	0.2	0.002	0.002	±1*	5×10^5 bits	Analog	Auto	LEM	LEM	No
Accelerometers	2.00	2.0	0.01	0.01	±0.3*/Sec. 2	24 bits	Analog	Auto	LEM	LEM	No
Body Temperature Sensors	0.30*	0.8	0.004	0.004	±0.2*	18 bits	Analog	Auto	LEM	LEM	No
Sphygmomnometer Aneroid	3.00	4.0	0.04	0.3	±5 mm	1 line	Verbal	Manual	LEM	LEM/ CM	Yes
ECG	0.14*	0.10	0.003	0.003	±20 mv	3×10^6 bits	Analog	Auto	LEM	LEM	No
Blood Pressure Subsystem	5.00	4.0	0.04	0.04	±5mm/ ±8 mm	2×10^5 bits	Analog & Verbal	Auto/ Manual	LEM	LEM/ CM	Yes
Heart Sounds	0.16	0.10	0.003	0.003	±5%	5×10^5 bits	Analog	Auto	LEM	LEM	No
Digital/Limb Plethysmograph	0.50	0.10	0.10	0.10	±5%/ ±10%	10^5	Analog	Auto	LEM	LEM	Yes
Respiration Pneumograph	0.14	0.10	0.003	0.003	±10%	10^4 bits	Analog	Auto	LEM	LEM/ CM	No
Ear Oximeter	0.05	1.0	0.0005	0.0005	±3%	1 line	Verbal	Manual	LEM	LEM	Yes

*Indicates instrumentation or equipment located in standard biomedical monitoring package

With the signal conditioners attached to the test subject, the low level, high impedance signals from the sensors to the signal conditioners can be conducted by short leads while high level, low impedance, signals are conducted over the long umbilical. All bodyworn signal conditioners have the physical characteristics of the standard NASA Gemini/Apollo units. The dimensions of these units, except for the ECG Signal Conditioner, are less than 2.3 in. x 1.5 in. x 0.415 in. These modules are of rugged,all-welded, and potted construction. The circuits are solid-state, stable, and nonsusceptible to external electrical noise.

System Components

Cardio Kit. - The sub-system consists of sensors, signal conditioners, attachment devices such as a signal-conditioner belt, and the subject-to-couch umbilical cable. All of this equipment folds into a small package which is stowed when the instruments are not in use for the experiments.

Electrodes and Packaging Kit. - The electrode system consists of a molded, thin-flanged flexible housing containing a silver-silver-chloride electrode which is stabilized relative to the skin by a rigid spacer. The electrodes are attached to the skin by Stomaseals which are washer-shaped disks with adhesive on both sides. The Stomaseals are packed in tubes from which they can easily be dispensed.

ECG/ZPn Equipment (Electrocardiograph and Respiration Rate).- ECG/ZPn consists of two transthoracic electrodes, one sternal ground electrode, and the connecting electrode leads used in common with an ECG and a ZPn signal conditioner.

All performance requirements are met with source impedances as high as 100,000 ohms in either input lead, and with dc voltages as large as 1 v peak-to-peak between 10 and 90 kc causes no performance degradation, and hence the circuit is capable of operating with the impedance pneumograph from a common pair of electrodes.

Thermistor Probe. - The oral temperature probe consists of a Yellow Spring instrument thermistor (Type 44111X) molded in a finger-formable probe which is placed in a hermetically sealed handle and cable connector assembly. The thermistor probe may be temporarily attached to the cardio-kit belt when not in use for temperature measurement. The pliability of the probe is advantageous in that it will readily conform to the oral characteristics of a given individual test subject.

Blood Pressure Equipment. - The blood pressure equipment consists of an arm cuff in which is positioned a microphone sensitive to Korotkow sounds, a hand-bulb pressure gage and Korotkow indicator, a signal conditioner, and intraconnecting cables and pneumatic tubes. The auscultatory blood-pressure technique with manual actuation of the brachial arm cuff is currently being employed on the Gemini program. A more precise indication of blood pressure is recorded and/or telemetered to ground from the analog output of the signal conditioner. The blood pressure (BP) signal conditioner

described below is a modified unit of the type currently flown in the Gemini program. It's main differences from the current model are as follows:

a. The output will be 0 to 5v instead of the 20 mv output now used on Gemini. The high level output will make it compatible with the rest of the bio-instrumentation system.

b. Provision will be made to power a Korotkow pulse indicator located on the arm cuff pressure gage.

The output signal will be an analog of the cuff pressure bleed-off curve on which will be superimposed the Korotkow pulses. Systolic blood pressure will be indicated by the first Korotkow pulse; diastolic pressure will be indicated by the last Korotkow pulse on the bleed-off curve.

Cardiac Output. - The method (impedance cardiographic-ZCG technique) has been recommended as the primary method because of the following reasons:

a. If cardiac output is the only parameter desired, the ZCG instrumentation requires little volume, is light in weight, and requires little power to operate.

b. The ZCG technique in no way obstructs the facial area with cumbersome masks and associated tubing.

c. The impedance cardiographic technique is being developed by NASA.

Two separate physiological parameters are measured by the thoracic impedance cardiac output method. In addition to the acquisition of thoracic impedance information, it is also necessary to sense the phonocardiogram. The cardiac output section thus contains a ZCG electrode harness assembly consisting of neck and diaphragm band electrodes, a PCG microphone, and ZCG and PCG signal conditioners.

The University of Minnesota-developed thoracic impedance technique begins with placing four band electrodes on the subject - two on the neck, one on the lower thorax, and one on the abdomen.

The two outer electrodes are excited by a 100 kHz constant current source and the thoracic impedance changes are monitored between the two inner electrodes.

The harness is fabricated from two horizontal elastic bands. Two metallic cloth electrodes are mounted on each band. Thin cloth strips connect the neck and chest elastic bands and these perform the important functions of maintaining a set electrode distance L for consecutive measurements. The electrode harness to be delivered to NASA with the flight-qualified Apollo system will also employ either rigid electrode separation bands or crotch straps to maintain the very critical distance between the neck and diaphragm electrodes.

The system is thus designed to allow simultaneous operation of both the impedance pneumograph and the impedance cardiograph. All output voltages are in the 0 to 5 v range with symmetrical operation on both sides of the 2.5 v point. Output impedances will not exceed 200 ohms within the bandpasses of interest.

Phonocardiograph (PCG). - The PCG microphone is a modified version of one developed by NASA/MSC for use on the Gemini program. This microphone utilizes a bimorphtype crystal slab mounted in a modified ECG electrode housing. The design of this unit is unique in that it is small, light in weight,
body using Stomaseal disks in the same way as for the ECG electrodes. The design incorporates a thin epoxy spray coating on the face of the crystal which is placed against the astronaut's body. The back face of the microphone is completely encapsulated with an epoxy resin. The phonocardiograph signal conditioner is basically a modified Apollo ECG signal conditioner.

Capacitance Plethysmograph. - The capacitance plethysmograph (CPG) consists of a spiral electrocapacitance screen, or mesh cuff, and a signal conditioner containing an oscillator, an amplifier, and a phase discriminator. Auxiliary equipment includes a calibration device.

The insulated copper screen, or mesh cuff, is placed around an extremity and forms one plate of a condenser. The other insulated shield screen, along with the skin, forms the other grounded plate. Changes in volume move the skin towards the fixed screen to change capacitance. This modifies the frequency and alters the output of the phase discriminator in direct proportion to the volume change.

The signal conditioner will contain the necessary oscillators and excitation sources for the mesh leg cuff. The capacitance variation due to volumetric changes under the cuff will modulate the carrier signal at the excitation bridge. The modulated carrier will then be amplified and detected to provide a 0 to 5 v analog of the volume at the signal conditioner output. The vhf necessary for this technique, however, may interfere with on-board telemetry.

Sensor Harnesses, Signal Conditioner Belt and Umbilical Cable. - The wiring harnesses for the cardio kit subsystem consist of several assemblies which serve to interconnect the signal conditioners, the power converter, the electrodes, and the temperature probe, and to provide electrical interfaces to the biometric console. The main harness consists of flexible, multiconductor, flat tape molded from translucent silicone rubber and containing an array of conductors of which some are shielded. To strengthen the tape which emerges from strain-relief blocks, stainless steel stranded conductor is molded into the tape along each edge. These steel braces terminate in the potting behind the connectors which couple to signal-conditioner modules and the main umbilical plug. Other harness assemblies provide the interconnections between the signal conditioners and the data acquisition sensors. The signal conditioner belt is basically a two-inch strip of cloth which is wrapped around the waist of the test subject just below the ZCG diaphragm electrode band.

Table 3. Centrifuge Instrumentation Requirements Summary

x = Continuous Monitoring
- = Displayed (to onboard monitor)
C.C. = Capacitance Coupler

ITEM	DESCRIPTION	TRANSMISSION	CHANNELS FOR RECORDING	ATTACHMENT	DEVELOPMENT
Std. Bio-Monit. -x EKG (HR) x Temp. x Phonocard -x Pneumograph (Resp. Rate)	Medical Monit and Data Criterion	Transmit	5	AgAgCl attached Ear Microphone Impedance	Apollo Hardware
x Plethysmograph	Vol. change in limbs	Transmit	1	Impedance	LRC
X Electro-oculogram	Vert. & horiz. nystagmogram	Transmit	2	5 leads AgAgCl	AAP
RATER & Sig.	Performance Tests	Wire, C.C.	4	None	GDC
x Accelerometer	Three Direction	Transmit	3	Strap	?
Perimeter	Peripheral Vision 80^o 20^o 0^o	Wire, C.C.	1	To couch	?
Ear Oximeter	O_2 Blo od Saturn tion	Transmit	1	Ear lobe	Waters
-x Blood Pressure	Automatic	Transmit	2	Arm	Evans AFB
Z & Y Race Head Restraint	Turn Rate	Wire, C.C.	2	To couch	GDC
NVDI	Rod & Sphere	Wire, C.C.	3	To couch	Pensacola NAMI
E.V.L.H.	Collimated Horizon	Wire, C.C.	2	Goggles	Pensacola NAMI
x Couch Position	X.Y.Z. & radial	Wire, C.C.	4	--	--
x R.P.M.	Onset & Holding	Wire, C.C.	1	--	--
Time	Date & Time	Wire, C.C.	1	--	--
Subject	Coded	Wire, C.C.	1	--	--
Eye Camera	Movie & Control	Film		Bite Bar	Pensacola NAMI
-x Television		Transmit	--		
- Voice					

Ear Oximeter. - The proposed ear oximeter is one similar to that being developed at NASA/Ames. The sensor detects the amount of light being transmitted from a light source through the blood in the ear. The associated electronics signal conditions the analog quantities detected by means of a red (0.65 millimicrons) and an infrared (0.79 millimicrons) filtered photocell. According to the engineers at Ames, with proper signal conditioning and data handling a calibrated output of blood oxygen saturation (possible accuracy to within 5 percent) is obtained. The blood pulse wave is also available, but is not normally calibrated.

Experiment Data Acquisition

The previous section has described a system that may be available for bio-monitoring and acquiring much of the physiological data required. There are, however, additional requirements for assessing the vestibular effects. Many of these instruments have been developed for experiment MO-53. Additional instrumentation will be required that is peculiar to the centrifuge. It is too early in the study program to define the new instrumentation in terms of power, weight and volume.

MO-53 instrumentation has been developed for the vestibular experiments included on Gemini and expended on Apollo Block II. Those portions of experiment MO-53 instrumentation applicable to the centrifuge are as follows:

Egocentric Visual Localization of the Horizon (EVLH). - This instrument is an adjustable line that has been collimated to a distance of infinity. It fits the subject as a set of goggles. A set of knobs adjusts the altitude and inclination of the line which indicates where the subject perceives the horizon. This setting is then recorded.

Oculogyral Illusion (OGI) Target. - This is a cube with illuminated edges. It serves as a target upon which the subject fixates. Cross-coupled accelerations (C. A.) produce the illusion that the cube or the subject is being reoriented in space. This C. A. is usually produced by the subject inclining his head rapidly from the upright to a shoulder. The movement is controlled by a bite bar.

Counter-rolling of the Eye. - This is recorded on film for later analysis. It is a measure of rotation about the pupil due to inclination of the head to the side (Y axis) and is believed to be an otolyth mediated reflex. Counter-rolling is measured in minutes of rotation so it is important to have the head-camera relation rigidly fixed.

Non-Visual Directional Indicator (NVDI). - This is a steel sphere with a magnetized rod. The sphere is divided into areas and the subject places the rod on the sphere in the position he perceives himself to be in space.

Couch Orientation. - Couch orientation instrumentation is required to record the exact position of the subject. It is also necessary to restrain the head so it is

fixed or can turn only in a given plane. The head restraint must also be instrumented so its position can be recorded in a way that permits magnitude and turn rate determinations.

Perceptual Motor Test. - A perceptual motor test such as that developed for NAS #9-5232 contract, using the Response Analysis Tester (RATER), is required to determine disorientation effects on performance following head turns. The test should be miniaturized for this purpose and automatic setting and recording incorporated. The present MSC contract NAS #9-6986 is using a series of tests incorporated in a single console. Other NASA space programs also require such an instrument and the console now being tested has the possibility of being miniaturized for that purpose.

Table 4. Physiological Data Management

MEASUREMENT	ANALOG O-SV		DEG.	GRAPH	BANDWIDTH (CPS)	AMPLIT. ACCURACY % SCALE	AUTOMATIC ACQUISITION
Electrocardiogram	X	&	X		.2-100	5	X
(Heart Rate)					(0-5)	1	X
Respiration Rate	X	&	X		.05-10		
Oral Temp.	X				0-1	1	X
Body Temp.	X				0-1	1	X
Blood Press.	X			X	0-100	4	X
Imped. Cardiogram	X				.1-40	2	X
Cap. Plethysmogram	X	&	X		.1-4	2	X
Eye Head Movements	X			X	0-10	1.5	X
Phonocardiogram	X				0-1	5	X
Cardiac Output	X	&	X		0-1	2	X
Body Mass	X	&	X	X	0-2	2	X
Art. O_2 Saturation	X	&	X		0-5	2	X

Recording Perimeter. - A recording and test system is required to determine "Grayout" in the subject in a manner that is objective. The position of the lights on the perimeter are 0, 23 and 80 degrees and must have controlled intensity.

Television Camera. - A television camera is required to monitor the subject all times that he is exposed to the rotation. The Apollo System includes a video camera. However, the requirements for the centrifuge monitoring may include a scan and zoom arrangement from a central location in order to visually confirm proper orientation and operation as well as subject "well being". Table 6 summarizes the TV monitoring requirement.

Table 5. Television Monitoring Requirements

The following chart illustrates the requirement for T V coverage during experiments and the posibility of installation.

EXPERIMENT	THE NEED	POSSIBLE EYE OBSERV.	OBSERV. OF OTHER BODY PARTS	POSSIBLE INTERFERENCE WITH OTHER INSTRUMENTS
Grayout	M	Yes	-	Perimeter Bite-Bar
Therapeutic	M	Yes	-	None
Angular Acceleration	D	Yes	-	None
Tilt Table	M	Yes	-	None
Semicirc. Canal Stimulation	M	Yes	-	Head Restraint, Rater, Light Periorbit. Electr
Linear Acceleration	D	No	Hands	Blinding Cover Otholith Goggle Bite-Bar
Oculogravic Illusion	D	No	Hands	Blinding Cover Otholith Goggle Bite-Bar
Eye Counter-roll	D	No	Hands	Photo Camera Bite-Bar
Re-entry Simulation	M	Yes	-	Display Panel
Mass Determination	D	Yes	-	None

M - Mandatory
D - Desireable

SRC TO FACILITATE WASTE COLLECTION

Introduction

Collection of human waste such as feces and urine in the absence of gravity is a relatively complex task. An artificial force can be created to direct the feces and urine to the appropriate collection receptacles thus preventing possible spacecraft contamination. One method providing the force required for waste collection consists of drawing air from the cabin into the collection device so flatus and fecal odors will not escape into the spacecraft atmosphere. Another possible method is performing the waste collection on an operating centrifuge utilizing centrifugal force to direct the waste into the collection chamber. The requirements of integrating a waste collection system with the centrifuge and the feasibility of such an approach have been examined. The results of this analysis are discussed in the following sections of this report.

Waste Collection Mechanics

Force Requirements. - The predominant force required for collection of urine and feces under zero gravity conditions is the force required to detach the fecal waste from the anal area and transfer it to the collection chamber. A force which will provide for fecal detachment should be adequate for fecal transfer. The detachment force may vary considerably and is dependent not only on fecal consistency but also on completeness of sphincter muscle contraction. It is of advantage to provide only minimum g-levels for generation of the detachment force in order to minimize power and spin-up time requirements. In addition, this will keep the centrifuge angular velocity at a minimum and will reduce the effect of cross-coupling due to head motions made during the waste collection process.

Since data on fecal detachment forces is essentially non-existent in the literature, an attempt was made to estimate the tensile strength of feces on an experimental basis. A number of samples of a canned dog food approximating feces in shape and consistence were tested to determine average tensile strength. Water was added to some of the samples to vary the consistency and the samples evidencing the greatest cohesiveness were chosen as representing the maximum detachment force requirement. The experimental data is presented in Table 6.

Table 6. Estimated Feces Tensile Strength

SAMPLE	BREAKING FORCE GRAMS	DIAMETER AT POINT OF DETACHMENT - INCH	TENSILE STRENGTH gm/in^2
1	36	1.065	40.6
2	29	0.797	45.7
3	19.5	0.765	42.5
4	16.5	0.668	47.2

Utilizing an average of the experimentally determined tensile strengths, a range of detachment forces was computed. This range represents detachment force values for minimum through maximum sphincter muscle contraction or closure. These detachment forces ranged from 1.36 grams to 12.45 grams. About 5 grams detachment force is required assuming a stool diameter midway between the maximum and minimum at the breakaway point.

To assure detachment and transfer of the feces, centrifugal force in excess of the detachment force must be generated. The centrifugal force exerted on a mass moving with uniform speed in a circle is given by the equation, $f = 4\pi^2 n^2 rm$, where n is angular speed in revolutions per second, r is the centrifuge radius from center of revolution to the seat bottom in inches, and m is the fecal mass in grams.

Since the centrifuge radius is fixed during waste collection operations, the only variables are speed and fecal mass. In general, the lighter the fecal mass, the higher the centrifuge speed required to generate a given detachment force. A fecal mass range from 69 grams to 18 grams was selected as being representative. The centrifugal force generated over this mass range by various centrifuge speeds was then calculated. The maximum and minimum centrifugal force generated is shown in Figure 17. Also plotted in this Figure are minimum and maximum detachment force requirements. Thus, for an assumed average detachment area diameter, the detachment force is 5 grams and from Figure 17 centrifuge speed requirements for waste collection range from about 6 to 10 rpm (.0785 g to .218 g).

<u>Optimum Collection Orientation.</u> - Proper orientation of both the waste collection device and the person defecating is important for maximum collection effectiveness. The optimum position for the person defecating is that approximating a squatting position with knees drawn up slightly higher than a normal sitting position. Current centrifuge couch design provides only minimal leg flexure. It would be desirable to modify the couch to allow the legs to be restrained in a more optimum position. Couch design should be such that the crew member is indexed over the collection device prior to defecation.

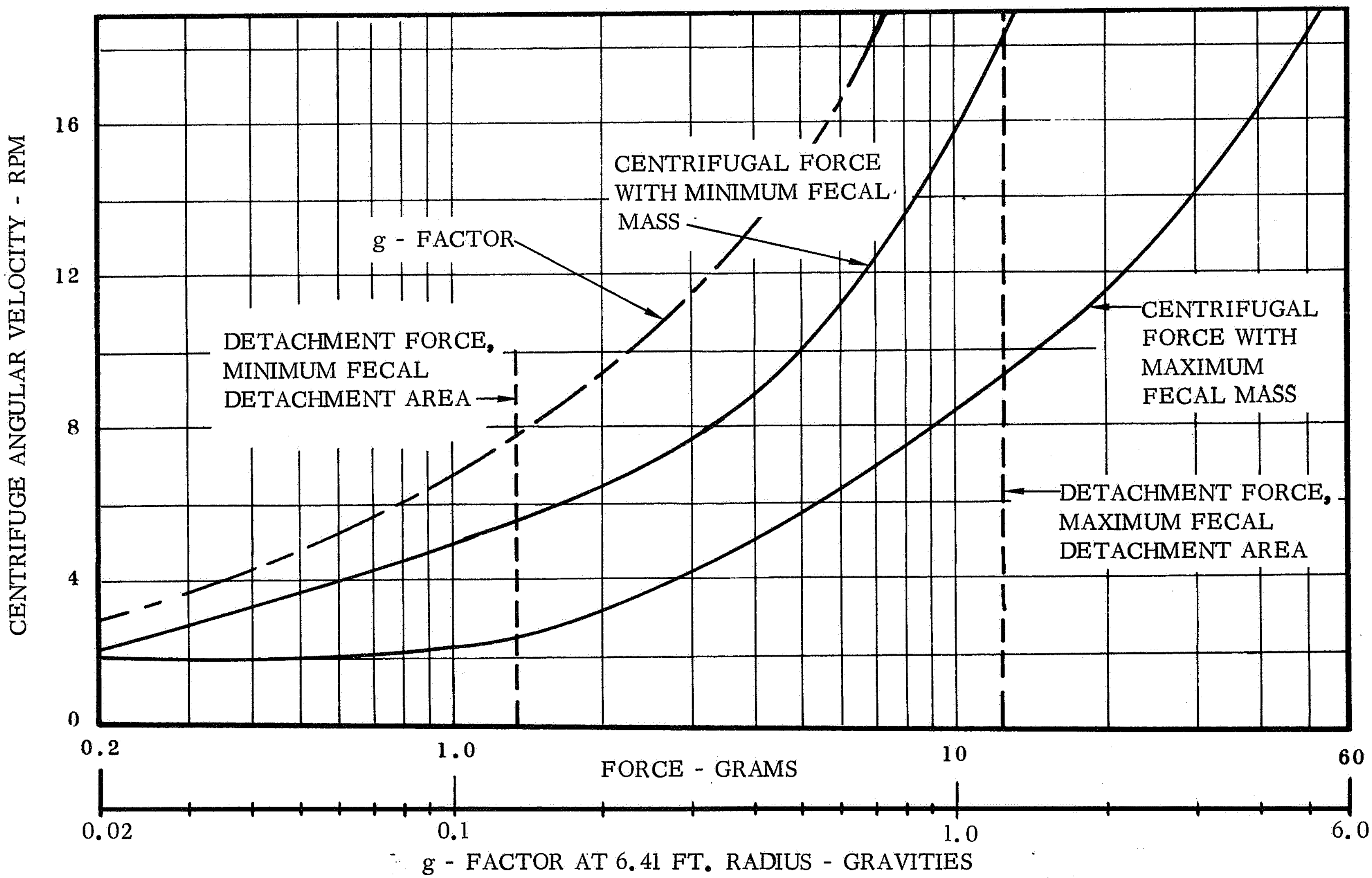


Figure 17. Centrifuge Speed Required for Waste Collection

The couch orientation should align the anal opening with the centrifugal force vector. The centrifugal force vector is in a direction normal to the circular path inscribed by rotation of the centrifuge. This orientation provides the maximum detachment force and minimizes fecal contact with the anal area.

In order to determine the best orientation for the feces collection receptacle and its size, it was necessary to analyze the trajectory of a fecal particle from the time of detachment until it impacts on the bottom of the collection receptacle. An equation was derived to determine the distance from the centerline of the receptacle bottom to the point of stool impact (see Appendix B for equation derivation). This distance, S, fixes the diameter of the collection canister and is given by:

$$S = \left(\frac{\sqrt{S^2 + R'^2 - R^2}}{R} - \tan^{-1} \frac{\sqrt{S^2 + R'^2 - R^2}}{R} \right) R'$$

where R is the length from the pivot point of the centrifuge to the seat bottom, 6.41 feet. R', 7.16 feet, is the length given by R plus the canister depth. A canister depth of 9 inches was considered adequate. It can be seen from this equation that the fecal trajectory is independent of depth. Solution of the equation gives a value of 3 inches for S. Thus, the collector diameter should be a minimum of 6 inches to assure fecal impact on the collector bottom.

Centrifuge Waste Collection System Design. - The centrifuge collection system contains hardware for urine and feces collection. The collection hardware is mounted to the centrifuge couch. The urine and feces collected on the centrifuge are transferred to the existing Apollo or S-IVB waste management system for disposal.

Urine Collection Subsystem. - The urine collection subsystem is shown in Figure 18. The major components of the urine collection subsystem are:

a. Urinal assembly
b. Flexible, vacuum - rated transfer hose
c. Stainless steel quick disconnected couplings
d. Non-porous rubber collection bag
e. Tubing shut-off clip
f. Collection bag retaining screen

The urinal is similar in shape and identical in operation to the military aircraft relief tube. The urinal is provided with a cover which seals vacuum-tight. Prior to urination, the urinal is secured in a holder mounted on the couch frame. Urine flows down the flexible tubing into the collection bag in response to centrifugal force. Upon completion of urination the transfer tubing is sealed by a metal clip and the entire urine assembly (urinal, tubing and collection bag) is removed from the centrifuge and

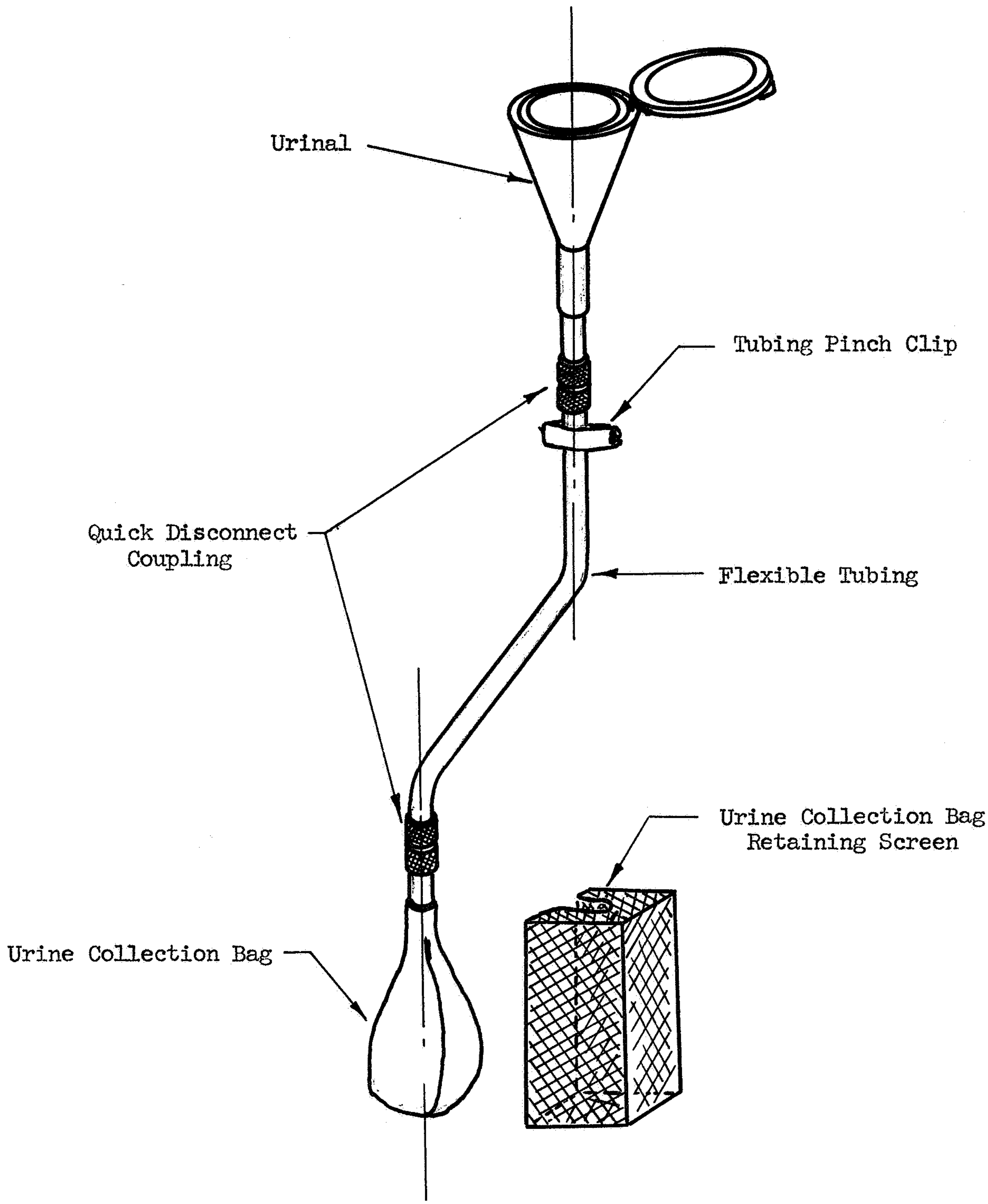


Figure 18. Urine Collection Device

is hand-carried to the existing waste management system. The urinal is detached from the transfer tubing at the closest quick disconnect fitting. The transfer hose end is then placed in the urinal of the existing waste collection system, the tubing pinch clip opened and the urine stripped from the collection bag and tubing. Following urine transfer, the collection bag is removed from the transfer tubing and stored in the existing feces dryer.

Fecal Collection Subsystem. - The major components of the fecal collection subsystem are:

a. Fecal collector assembly
b. Fecal collection bags
c. Flexible gas transfer line
d. Activated charcoal filter
e. Blower and associated electrical hardware

These components are shown in Figure 19. The fecal collector is attached to the couch seat pan in such a manner as to provide for quick attachment and detachment. The couch seat pan has a cutout to allow passage of the feces into collector. This cutout is filled with a contoured plug when the centrifuge is not being used for waste collection. The couch seat pan is contoured in such a fashion that the anal area of the astronaut is indexed over the collector and the buttocks slightly spread to minimize fecal contact.

To prevent contamination of the compartment atmosphere a small amount of cabin air is pulled through the collector, the collector bag and finally through a charcoal filter where odors and organic vapors are removed. The air is then discharged back into the cabin. The necessary suction to pull the air through the collector assembly is supplied by a small blower. This blower provides a flow of about 3 cfm and has a power requirement of 20 watts.

The collection bag is made of a porous teflon material as described in Reference 5. This material retains liquids and solids but is permeable to the collection gas and water vapor. The bag is bonded to a vinyl cuff which fits over the top of the collection canister and holds the bag in place when the collector assembly is fastened to the seat pan. The bag also contains a vinyl flap on one side which is used as a tuck-in enclosure after the collection bag has been used.

The collection canister, charcoal filter and blower are designed into one assembly with quick disconnect electrical fittings so that the entire assembly may be removed from the centrifuge when not in use. The used bags are transferred manually to the existing feces dryer for storage.

Centrifuge Waste Collection System Integration

Integration With Space Research Centrifuge System. - Addition of a waste

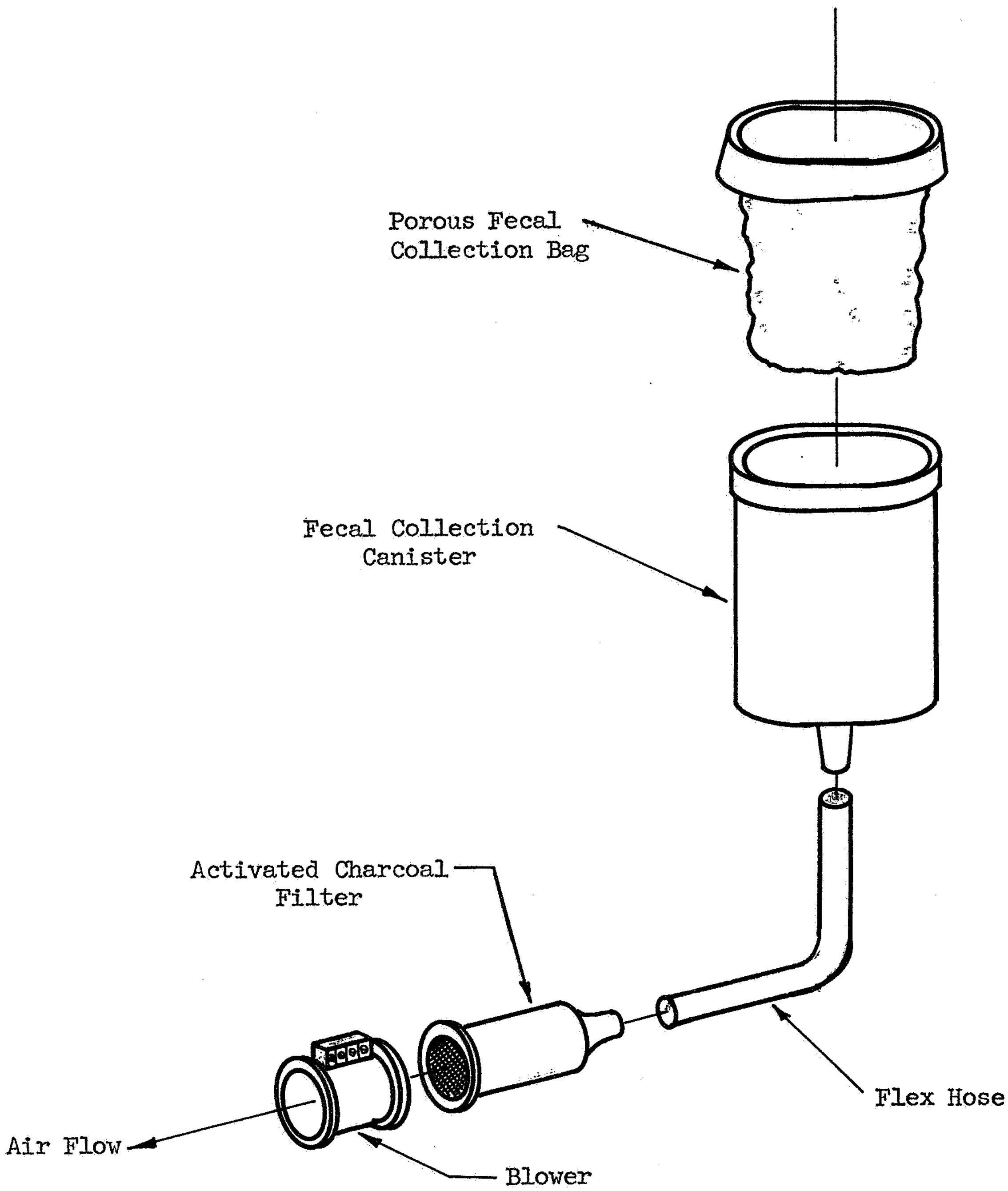


Figure 19. Fecal Collection Device

collection unit to the space research centrifuge imposes a number of added requirements in terms of general centrifuge design and couch modification. Added centrifuge design requirements include handling the added weight of the waste collection system and providing the power necessary to operate the waste management system blower. The couch modifications required are:

a. Modify couch design to provide an opening over the collection canister. Provision should be made for closing this opening when not in use.

b. Modify couch design to aid indexing individual over fecal collector.

c. Add stirrups to couch to provide foot restraint while improving individual's position for defecation.

d. Modify restraint harness to enable individual to clean anal area with tissue while centrifuge is operating. Provide handholds for body positioning to aid in this operation.

Integration with Existing Waste Management System. - The design of the centrifuge waste collection system must be compatible with the Habitability Experiment M-487 Waste Management System. The M-487 waste management system provides for collection of both urine and feces. The urine collector or urine volumetric measuring device accepts the urine of the astronaut, gives an automatic readout of the urine volume, obtains a 75 cc sample and dumps the remaining urine to space vacuum. The urine dump line and dump port are heated to prevent freezing and clogging. The urine collection bag used on the centrifuge is designed so that it can be removed from the centrifuge and transferred to the M-487 waste management system. The bag design facilitates expulsion of the collected urine into the urine volumetric measuring device without spillage. Empty urine bags are dried in the drying unit and stored in the same storage unit used for storing dried urine samples and dried feces.

The fecal collection unit portion of the M-487 waste management system consists of a fecal collection canister, a pump providing suction to keep the feces contained within the canister, an activated charcoal filter to remove organic gases and odors from the air drawn through the feces collection unit by the pump, a fecal drying unit and a holding unit for storage of the dried feces.

The fecal collection device suggested for use on the centrifuge is similar in operation except that airflow is required only to prevent the escape of noxious gases and odors from the collection unit rather than to provide for feces detachment and transfer. Consequently, a low airflow is required. Fecal bags for the centrifuge shall be constructed of the same porous material used in the M-487 system. In addition the bags shall be color coded and have provisions for marking on the bag similar to those used in the M-487 system.

Integration with the Centrifuge Experiment Program. - The feasibility of utilizing the centrifuge for waste collection depends, for a large part, on the time required for

Table 7. Centrifuge Waste Collection Procedure

STEP NUMBER	PROCEDURE DESCRIPTION	TIME REQUIREMENT MINUTES
1.	Remove urine and feces bags from storage	0.17
2.	Install urine bag on urine collection device	0.50
3.	Attach urine collection device to centrifuge	0.33
4.	Install fecal collection bag	1.00
5.	Remove centrifuge couch seat cover	0.17
6.	Open top of urine collector	0.17
7.	Turn on waste collection system blower	0.05
8.	Crew member removes sufficient clothing to perform defecation	0.50
9.	Crew member mounts centrifuge couch and assumes required position	0.50
10.	Restraint system adjustment	0.25
11.	Centrifuge spin-up	0.10
12.	Defacation and urination	5.0
13.	Cleansing of anal area	0.50
14.	Close urine collector top	0.10
15.	Seal urine collection bag	0.50
16.	Centrifuge spin down	0.09
17.	Removal of restraint harness	0.10
18.	Dismount from centrifuge couch	0.25
19.	Replace clothing	0.50
20.	Remove urine bag and collector from centrifuge waste management system	0.25

Table 7. Centrifuge Waste Collection Procedure (Cont'd)

STEP NUMBER	PROCEDURE DESCRIPTION	TIME REQUIREMENT MINUTES
21.	Remove and seal fecal collection bag from centrifuge waste management system	0.50
22.	Shut-off waste management system blower	0.05
23.	Secure waste management system	0.17
24.	Carry urine and feces bags to M-487 waste management system (WMS)	1.00
25.	Close M-487 WMS urine dump valve	0.10
26.	Repressurize M-487 WMS urine collector line	0.10
27.	Open M-487 WMS urinal cover	0.17
28.	Disconnect centrifuge WMS urinal from urinal collection line and bag	0.17
29.	Open M-487 WMS urine dump valve	0.10
30.	Place centrifuge urine bag line in M-487 WMS urinal	0.05
31.	Open urine bag line sealing clip	0.05
32.	Strip urine from bag and line	0.50
33.	Remove urine bag line from M-487 WMS urinal and close urinal cover	0.17
34.	Disconnect centrifuge urine bag from line	0.05
35.	Place empty urine bag and feces bag in M-487 dryer	0.50
36.	Connect urine collection line to centrifuge WMS urinal	0.05
37.	Connect centrifuge urine collection assembly to M-487 urinal vacuum line	0.05
38.	Secure centrifuge urine collection assembly	0.10
	Total Time	14.46 Minutes

the entire waste collection procedure and the effect of this time requirement on the centrifuge experiment program. The entire waste collection procedure was broken down into steps and the time requirement for each step analyzed to arrive at the total time required for each waste collection use. This time-line breakdown is shown in Table 7. The total time required per defecation for waste collection procedures is 14.46 minutes each. Assuming one defecation per day per crew member, a total time of 43.38 minutes will be required per day for the crew of three. Collection of urine alone requires much less time. Step numbers 4, 5, 7, 8, 10, 13, 19, 21, and 22, shown in Table 8 are eliminated and step Number 12 is reduced to one-half minute. It is assumed that each crew member urinates three times per day exclusive of that occurring during defecation. The time required per urination is 6.44 minutes or a total of 57.96 minutes per day for the three man crew for urination. The total waste collection time required per day is then one hour and forty-one minutes. Some of this time includes procedures which do not involve the centrifuge equipment. Step numbers 24 through 38 are carried out outside of the centrifuge module and do not restrict use of the centrifuge for other uses. These steps take about 3.16 minutes per man per defecation or urination. This amounts to thirty-eight minutes per day. Thus, the waste collection procedure restricts the use of the centrifuge for other purposes a total time of one hour and three minutes per day.

Table 8 shows the tentative experiment schedule for the T-010 mission. The planned activity for this facility can be as high as eight hours use per day. This does not exclude the use of the facility for waste collection but severely limits its availablity for non-scheduled activities. Any contamination of the area would of necessity have to be cleaned up immediately. Odors are known to effect rotation tolerance and the experimental requirements should have precidence for the centrifuge.

It has been assumed that the centrifuge is primarily for experimental use; this is not necessarily true. The centrifuge, either in the S-IVB or attached to the cluster could be used for a waste collection device after the T-010 mission is completed. In this event, the concept increases in feasibility as the conflict in time sharing disappears.

Failure Modes and Effects. - Failures which could reduce the effectiveness of the centrifuge waste collection system include centrifuge enclosure contamination with human waste products, accidental detachment of waste collection equipment during rotation, and centrifuge failure.

Escape of urine, feces or organic gas from the waste collection container into the centrifuge enclosure would present a severe operational hazard. If this escape occurs during centrifuge rotation, the material would be distributed over most of the centrifuge area. With proper design, the possibility of urine or feces loss during rotation should be remote. Urine or feces could also escape into the centrifuge enclosure by leakage from the collection bag during bag closure and transfer or in the event of bag rupture. Again, proper equipment design should minimize this potential method of contamination. Failure of the waste collection system blower could allow the diffusion of organic gases and odors into the centrifuge enclosure. It may be desirable to include a redundant blower in parallel for the waste collection system to preclude this possibility.

Table 8. T-010 Experiment Schedule

MISSION DAY	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
GRAYOUT							X							X							X							X							X							X			
							X							X							X							X							X							X			
THERAPEUTIC																																				X	X	X	X	X	X	X	X	X	X
ANGULAR ACCEL.				X			X				X							X					X				X					X						X				X			
								X							X							X							X							X							X		
								X							X							X							X							X							X		
								X							X							X							X							X							X		
TILT TABLE					X							X							X							X							X							X					
					X							X							X							X							X							X					
					X							X							X							X							X							X					
SSC STIM.			X							X							X							X							X							X							
			X							X							X							X							X							X							
			X							X							X							X							X							X							
LINEAR ACCEL.	X								X																					X															
	X															X																					X								
	X																						X																				X	
OCULOGRAVIC ILLUSION	X								X																					X															
	X															X																					X								Comb. experiment
	X																						X																				X	
COUNTER ROLL	X								X							X																					X								
	X																																											
	X																						X																				X	
RE-ENTRY SIMULATION							X							X							X						X								X					X					
MASS DETER-MINATION						X							X							X							X							X							X				
						X							X							X							X							X							X				
						X							X							X							X							X							X				

Contamination of the centrifuge enclosure with urine or feces is highly undesirable both from an esthetic standpoint and maintaining centrifuge equipment. Urine is extremely corrosive and is hygroscopic. Metal parts, particularly electrical switches and relays, could be severely damaged. Such vulnerable areas should be protected with coating or enclosure.

Surfaces within the centrifuge enclosure should be designed for easy cleaning. Unless removed, urine or fecal material adhering to centrifuge surfaces will become a source of bacterial contamination. Odors developed as a result of bacterial growth could change rotation tolerance of the subjects considerably. Crew enthusiasm for the experiments could also be expected to diminish under such circumstances.

Both urine and fecal collection equipment would be attached to the couch during use. If such items are heavy or sharp, accidental release from the centrifuge at 10 rpm could cause puncture of the centrifuge enclosure and result in loss of pressure. Proper equipment design including attachment and restraining devices as well as rigid attention to waste collection equipment installation and checkout procedures prior to operation can minimize this failure. Exteriors of attachable equipment should be constructed of resilient materials whenever practical.

Were the centrifuge used for waste collection alone, many of these factors could be avoided by enclosing the couch in a capsule and the centrifuge system could be much simpler than the present concept. If the M-487 should show a requirement for a waste collection system having centrifugal force, the internal centrifuge for T-010 could incorporate the required alterations on the basis of an experiment or feasibility test. Part of such a test would be to purposely discharge a substance to determine the choice of clean-up procedures. The test materials would be non-toxic, biologically inert substances specifically chosen for easy identification.

Since the centrifuge waste collection unit requires centrifugal force for the transfer of urine and feces to the collection bags, failure of the centrifuge would essentially prohibit further use of that waste collection system. If failure occurs during a waste collection procedure, some escape of body wastes from the collector could occur. Back-up methods for waste collection which can be used under zero gravity conditions appear necessary.

Conclusions

In order to evaluate the desirability of utilizing the centrifuge for waste collection, a comparison was made between the M-487 experiment Waste Collection System and the waste collection system proposed for use with the centrifuge. This comparison is shown in Table 9.

It was concluded from this comparison that if the waste collection function can be accomplished in a satisfactory manner utilizing the M-487 experiment waste collection system the centrifuge can be made to serve as a convenient back-up or supplementary collection device. The penalties associated with couch modifications and experiment conflict can be resolved if the need for such an application arises.

Table 9 . Waste Collection System Comparison

Consideration	M-487 Waste Collection System	Centrifuge Waste Collection System
1. Collection Mechanics	Force necessary for feces detachment and feces and urine transfer provided by air flow. Waste containment is expected to be satisfactory.	Force necessary for feces detachment and feces and urine transfer provided by centrifuge operation. Waste containment is expected to be satisfactory.
2. Personal Sanitation	No provision for washing of penile or anal area. Cleansing of anal area by tissues only.	No provision for washing of penile or anal area. Cleansing of anal area by tissues only and must be accomplished during centrifuge revolution.
3. Waste Handling	Most urine collected is evacuated directly to space vacuum. Only urine samples are transferred to feces dryer. Fecal collection bag manually closed and transferred to feces dryer.	Urine transferred from collection bag used on board centrifuge to existing urinal (M-487 WMS). Empty urine bag plus sample transferred to dryer. Fecal collection bag removed from centrifuge collection unit, manually closed, transferred to dryer (M-487 WMS).
4. Contamination Potential	Contamination potential fairly small. Airflow collection minimizes opportunity for escape of organic gases and odors. Some possibility for contamination during manual transfer of urine and feces.	Contamination potential somewhat higher than M-487 waste collection system due to manual transferring of urine from centrifuge to M-487 urinal and then the urine sample to the dryer. Airflow during collection also required to prevent escape of organic gases and odors into the atmosphere.
5. Crew Acceptability	With the exception of airflow, this method of collection, closely approximates that normally used on earth. Manual transfer of urine and feces is required but manual manipulation or kneading of disinfectant through the feces is not required. Crew acceptability should be fairly high.	Crew acceptability is not expected to be high. Psychological adaptation to defecation while rotating at speeds up to 10 RPM may be difficult. By necessity, the astronaut on the centrifuge cannot be afforded any privacy while defecating. Manual cleaning of the anal area with tissue during rotation may be a difficult maneuver. Manual transfer of urine and feces should not be objectionable to the crew.
6. Equipment Modification	No modification of equipment required. Existing waste management system design will be used.	Modification of centrifuge couch design and centrifuge internal power distribution system required. Centrifuge waste management system detail design and development required.
7. Experiment Disruption	No experiment disruption is expected.	Centrifuge use would be restricted to waste collection about one-hour per day. This time however represents usage of the centrifuge twelve times per day. In addition, when the centrifuge is used for waste collection, an additional man is required to operate the centrifuge, thus two men's time is lost whenever urination or defecation is necessary.

EXPERIMENTAL PROTOCOLS AND TIME LINE ANALYSIS FOR T-010 EXPERIMENTS

Introduction

To approximate the time and power requirements for experimental task T-010, a time analysis was completed for each T-010 experiment. This analysis was then extended to encompass a 45-day mission as specified in the contract. The prime consideration in this analysis was the experimental design to obtain physiological data as outlined in the Experiment Development section.

Couch orientations combined with arm translations are physically limited by a 108 inch radius maximum. Since certain couch orientations when combined with arm translations exceed the 108 inch radius maxima, all centrifuge orientations will be accomplished with the centrifuge stopped and the observer physically present.

The couch and centrifuge have common axes only when the couch is parallel to the arm and facing up. To avoid confusion, all orientations of the couch are made relative to the axes of the subject, not the centrifuge. The centrifuge configuration is shown in Figure 20.

At the commencement of each experimental day it will be necessary to attach all biomonitoring leads to the subjects. The leads to be used will be dictated by the experiments outlined for that mission day. It is assumed that all biomonitoring leads will be good for the duration of the mission day. Calibration of leads will be accomplished at the beginning of each experiment.

Detailed Time Analysis for Each T-010 Experiment

To determine the measurements required to obtain the needed physiological data, each experiment has been analyzed for centrifuge requirements and accessory equipment. Each procedure has been further analyzed to provide maximum safety and well-being of the subject. Within the limitations, a detailed time analysis has been completed for each experiment.

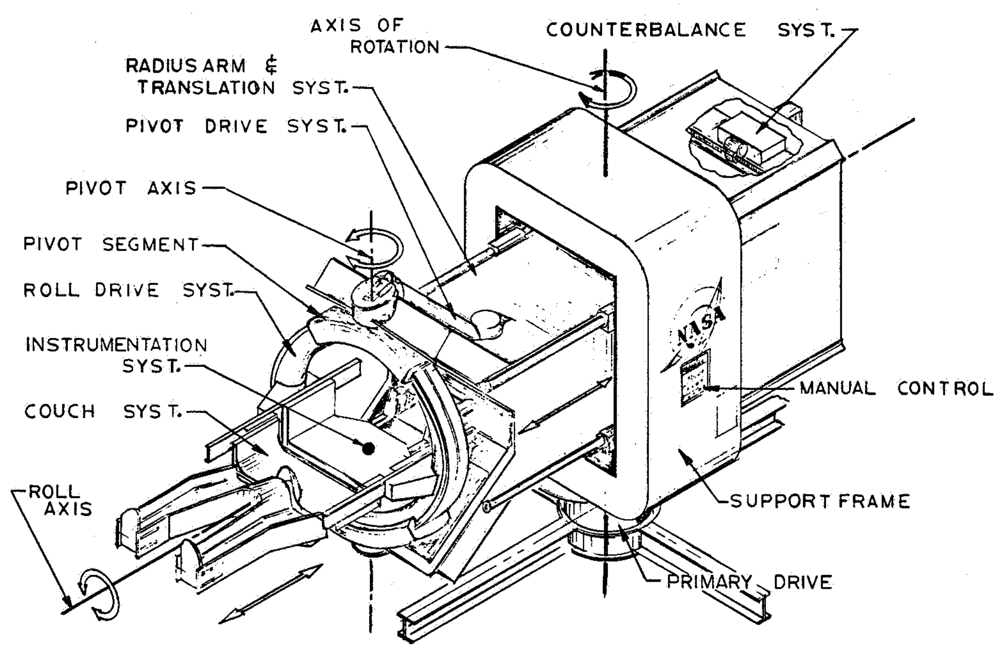


Figure 20. Ground Based Centrifuge

Table 10. Experiment Procedure:

T-010A - Study of Grayout Thresholds by Use of Peripheral Vision Lights

Subjects: 1 and 2.

Days of Test: 7, 14, 21, 28, 35, 42.

Time Required: Preparation, 56 min.; Test, 8 min.; Clean up, 15 min.

Centrifuge Position: arm rotation, 96" radius to feet.

Couch Orientation: radial with legs out

RPM: 47; Number spin Ups Required, Total: 12

Stability Required: None*

Acceleration: 0.082 rad/sec^2 = 4.7°/Sec.^{2}

g Onset: 0.1 g/sec.; g Required: 6 (ft)

Experiment Instrumentation: lights 0°, 23°, 80° from axis of vision
light illumination control
EOG

Subject Preparation Required: EKG, EOG, BP

Possible Hazards: loss of consciousness
petechial hemorrhage
hemorrhoids.

*Presently assumed that cross coupling below 60°/sec.^{2} is tolerable. (See Volume IV)

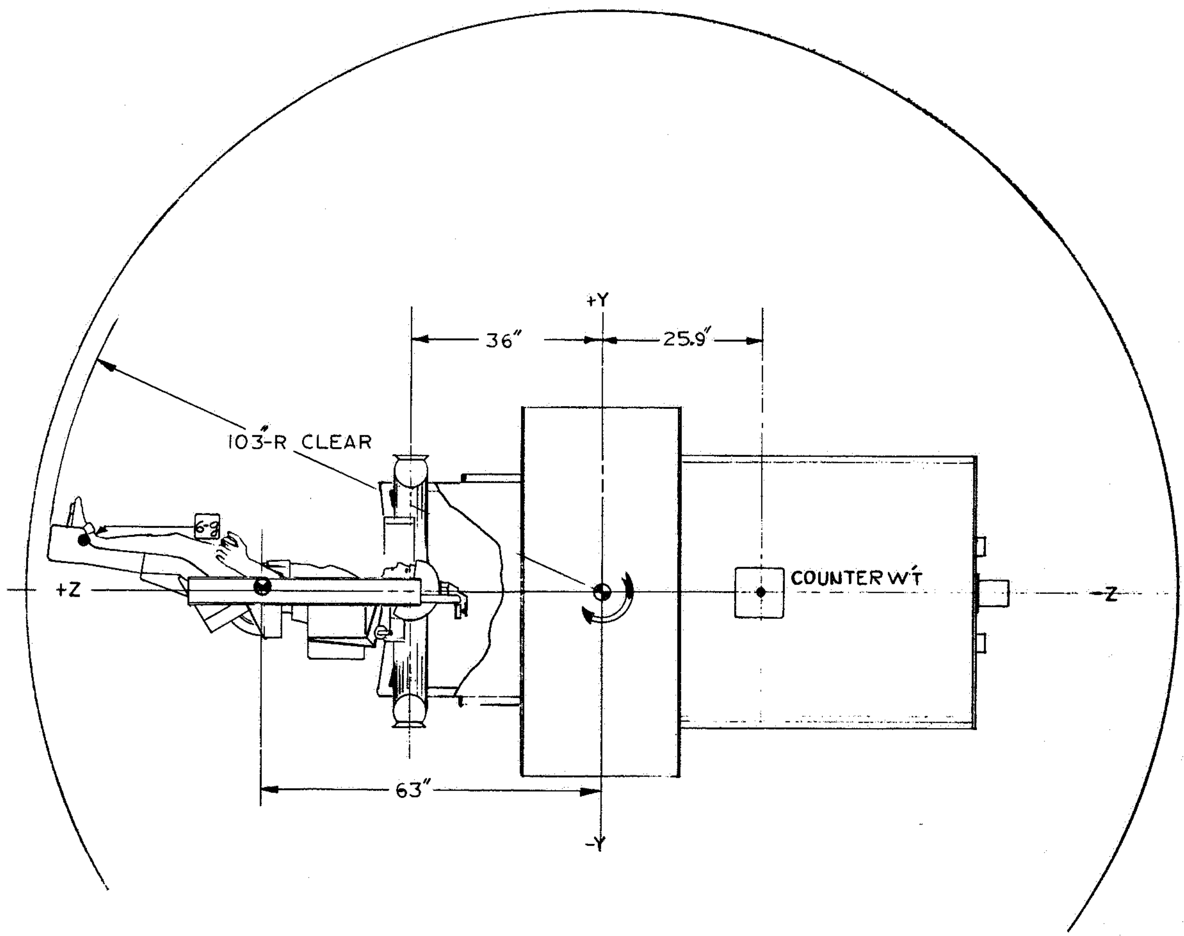


Figure 21. T-010A, Grayout Sensitivity Thresholds

Table 11. T-010A - Time Analysis

		minutes
Preparation:	subject into couch	3
	adjust head restraint	10
	adjust and tighten straps	3
	rotate couch 90° left about z axis	2
	attach peripheral light device	15
	observer return to console	5
	calibration of monitoring leads:	
	horizontal EOG	10
	vertical EOG	10
	blood pressure check	5
	EKG check	3
Experiment:	spin up (6 g at 0.1 g/sec.)	2
	test	4
	spin down (-0.1 g/sec.)	2
Clean up:	observer to centrifuge	5
	reorient couch	2
	loosen straps	1
	loosen head restraint	3
	remove subject from couch	2

Table 12. Experimental Procedure: T-010B - Therapeutic Support

Subjects: 1 and 2.

Days of Test: (1) 36 - 45; (2) 4, 7, 11, 18, 23, 27, 32, 38, 42

Time Required: Preparation, 36 min.; Test, 20 min.; Clean up 15 min.

Centrifuge Position: 68.5" radius to feet

Couch Orientation: radial with legs up full

RPM: 53; Number Spin Ups Required: 40

Stability Required: None

Acceleration: 0.139 rad/sec^2 = 7.97°/Sec.^{2}

g Onset: 0.1 g/sec

g Required: 4 (at feet)

Experiment Instrumentation: plethysmograph

Subject Preparation Required: EKG, BP attachments

Data to be Recorded: EKG, BP

Possible Hazards: syncope

petechial hemorrhage.

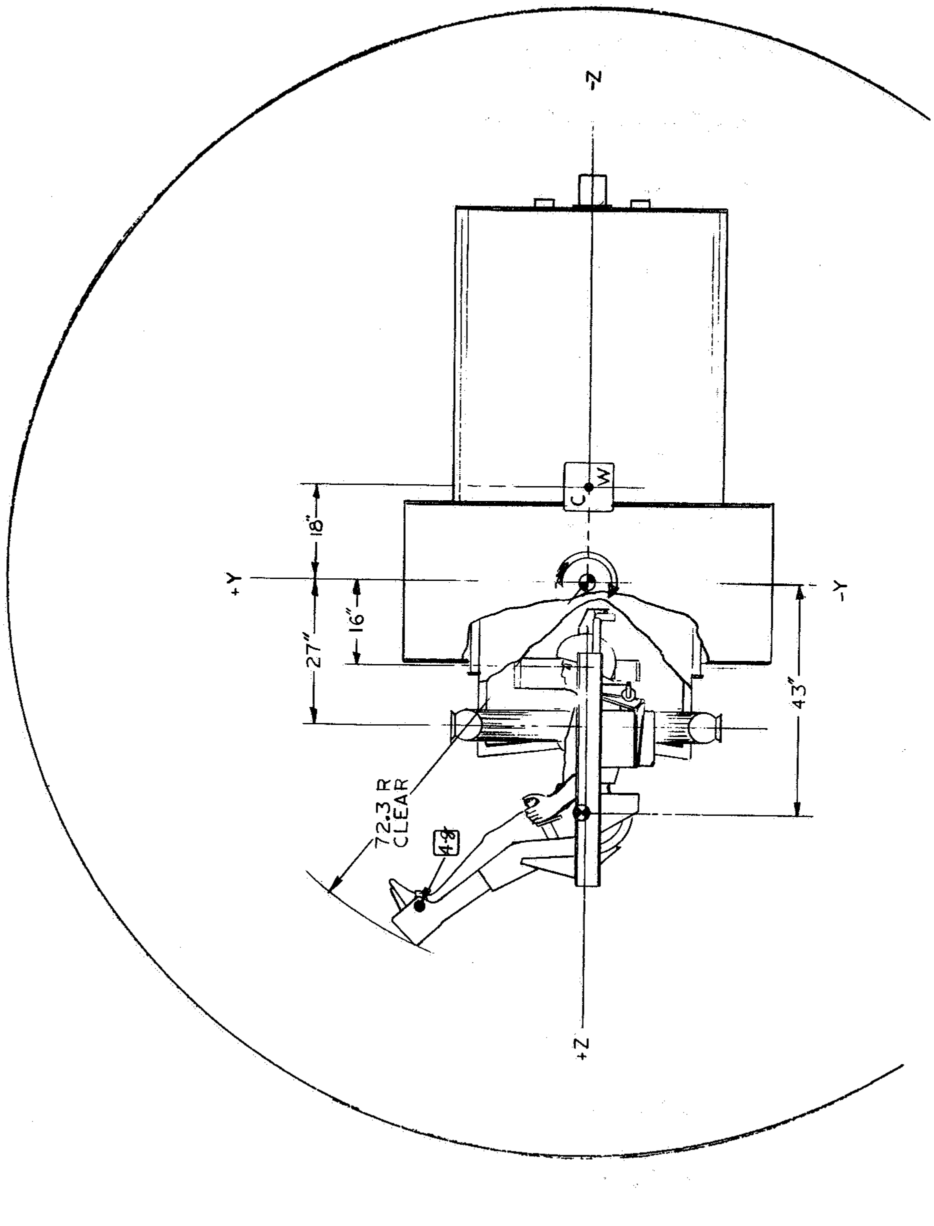


Figure 22. T-010B, Therapeutic

Table 13. T-010B - Therapeutic Support Time Analysis

		minutes
Preparation:	get subject into couch	3
	adjust head restraint	10
	adjust leg position to up	3
	adjust and tighten straps	3
	rotate couch 90° left about z axis	2
	translate arm to position head 16" from center rotation	2
	observer to console	5
	monitoring head calibration:	
	blood pressure	5
	EKG	3
Experiment:	spin up (54 rpm at 0.1 g/sec)	2
	test	20
	spin down (-0.1 g/sec)	2
Clean up:	observer to centrifuge	5
	reorient couch	4
	loosen straps	1
	loosen head restraint	3
	remove subject from couch	2

Table 14. Experimental Procedure:
T-010C - Threshold Levels of Sensitivity for Angular Acceleration

Subjects: 1, 2 and 3.

Days of Test: 8, 15, 22, 29, 36, 43

Time Required: Preparation, 62 min.; Test, 30 min.; Clean up, 11 min.

Centrifuge Position: head 27" from center of rotation

Couch Orientation: radial with legs out

RPM: 0 - 6; Number Spin Ups Required: 18

Acceleration Rate: 0.1^{o} to $1.0^{o}/sec^{2}$ (z axis rotation)

Stability Required: order magnitude less than threshold

Experiment Instrumentation: on-board computer

illuminated target

VOG

left and right indicator buttons

Subject Preparation Required: EOG, EKG and BP leads

Data to be Recorded: change in acceleration

subject's response and latency

VOG

Possible Hazards: none.

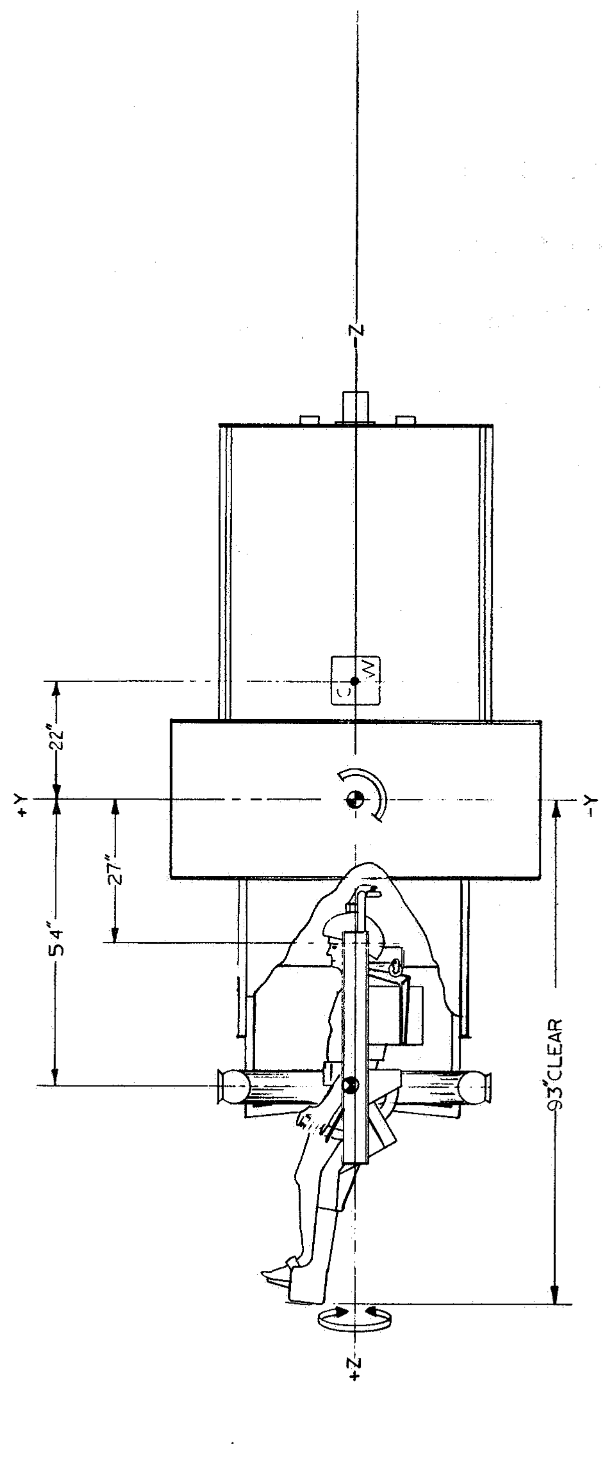


Figure 23. T-010C, Angular Acceleration Threshold

Table 15. T-010C - Threshold Levels of Sensitivity for Angular Acceleration - Time Line Analysis

		MINUTES
Preparation:	get subject into couch	3
	adjust head restraint	10
	adjust and tighten straps	3
	attach illuminated target device	15
	rotate couch 90^{o} left about z axis	2
	observer to console	5
	monitoring leads calibration	
	horizontal EOG	10
	vertical EOG	10
	blood pressure	3
	EKG	5
	direction indicator	2
	activate computer	2
	darken area	1
Experiment:	computer sequence	30
Clean up:	observer to centrifuge	5
	loosen straps	1
	loosen head restraint	3
	remove subject from couch	2

Table 16. Experimental Procedure: T-010D - Tolerance To Tilt Simulation

Subjects: 1, 2 and 3

Days of Test: 5, 12, 19, 26, 33, 40

Time Required: Preparation, 35 min.; Test, 27 min.; Clean up, 15 min.

Centrifuge Position: couch center 48" from center of rotation

Couch Orientation: (a) circumferential (back)

(b) tilt toward axis with legs one-half up

Number Spin Ups Required: 18

RPM (rotation) 27

(tilt) 0.375

Acceleration: 0.141 rad/sec.^{2}, 0.0196 rad/sec.^{2}

g Onset: 0.05 g/sec.

g Required: 1 g at heart

Stability Required: yes

Experiment Instrumentation: real time display of heart rate and blood pressure

blood pressure measurement

EKG measurement

Subject Preparation Required: block visual clues

Data to be Recorded: heart rate and blood pressure
1) 5 min. baseline in horizontal
2) during test

Possible Hazards: syncope.

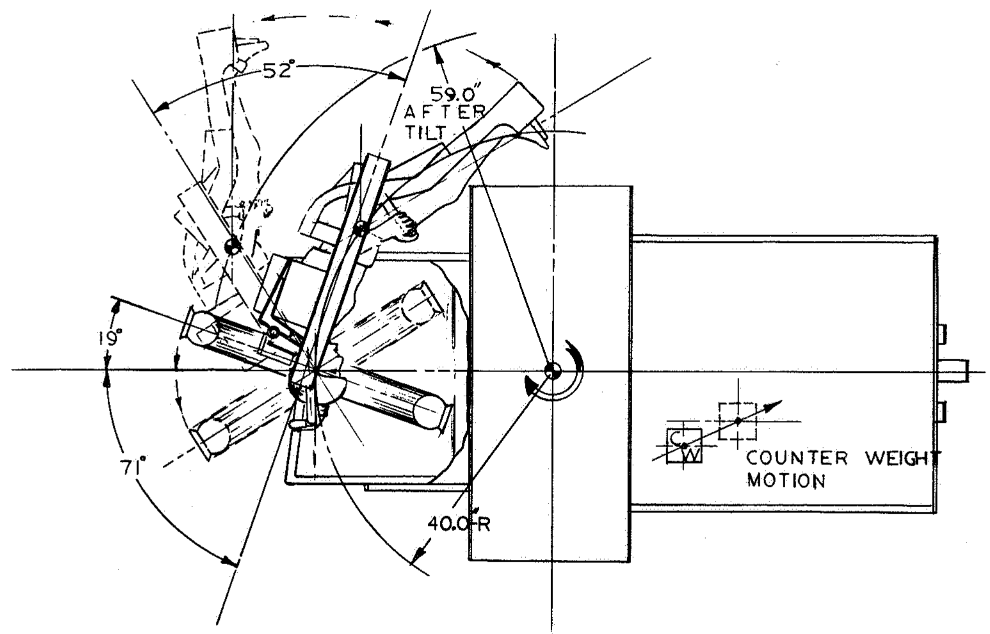


Figure 24. T-010D, Tolerance to Tilt Simulation

Table 17. T-010D - Tolerance To Tilt Simulation- Time Line Analysis

		MINUTES
Preparation:	get subject into couch	3
	adjust head restraint	10
	adjust and tighten straps	3
	block vision	2
	rotate couch about x axis 90^{o} and 90^{o} y axis to give circumferential position with eyes in board	4
	observer to console	5
	monitoring leads calibration	
	blood pressure	5
	EKG	5
Experiment:	spin up (0.1 g/sec.)	1
	test (tilts toward axis)	25
	spin down (0.1 g/sec.)	1
Clean up:	observer to centrifuge	5
	reorient couch	2
	unblock vision	2
	loosen straps	1
	loosen head restraint	3
	remove subject from couch	2

Table 18. Experimental Procedure:
T-010E - Semicircular Canal Stimulation and Coupled Angular Velocities

Subjects: 1 and 2

Days of Test: 3, 10, 17, 24, 31 38

Time Required: Preparation, 93 min.; Test, 312 min.; Clean up, 35 min.

Centrifuge Position: head: O radius, 45" radius from center

Couch Orientation: a) facing tangetial

b) Facing normal

c) 45° between a and b

d) legs one-half up

RPM: 4 - 10; Number Spin Ups Required: 144

Acceleration: a) 1.68 rad/sec.^{2}, b) 0.91 rad/sec.^{2}, c) 0.65 rad/sec.^{2}

d) 0.37 rad/sec.^{2}

g Onset: 0.1 g/sec.

g Requirements (at feet): a) 0.025, b) 0.046, c) 0.161, d) 0.278

Stability Required: yes

Experiment Instrumentation: four colored lights collimated to 1° angle

buttons on box corresponding to each light

head turn restraint for x and y

Subject Preparation Required: none

Data to be Recorded: head turn rate

vertical and horizontal oculograms (VOG)

performance

latency response

eye fixation time

Possible Hazards: nausea.

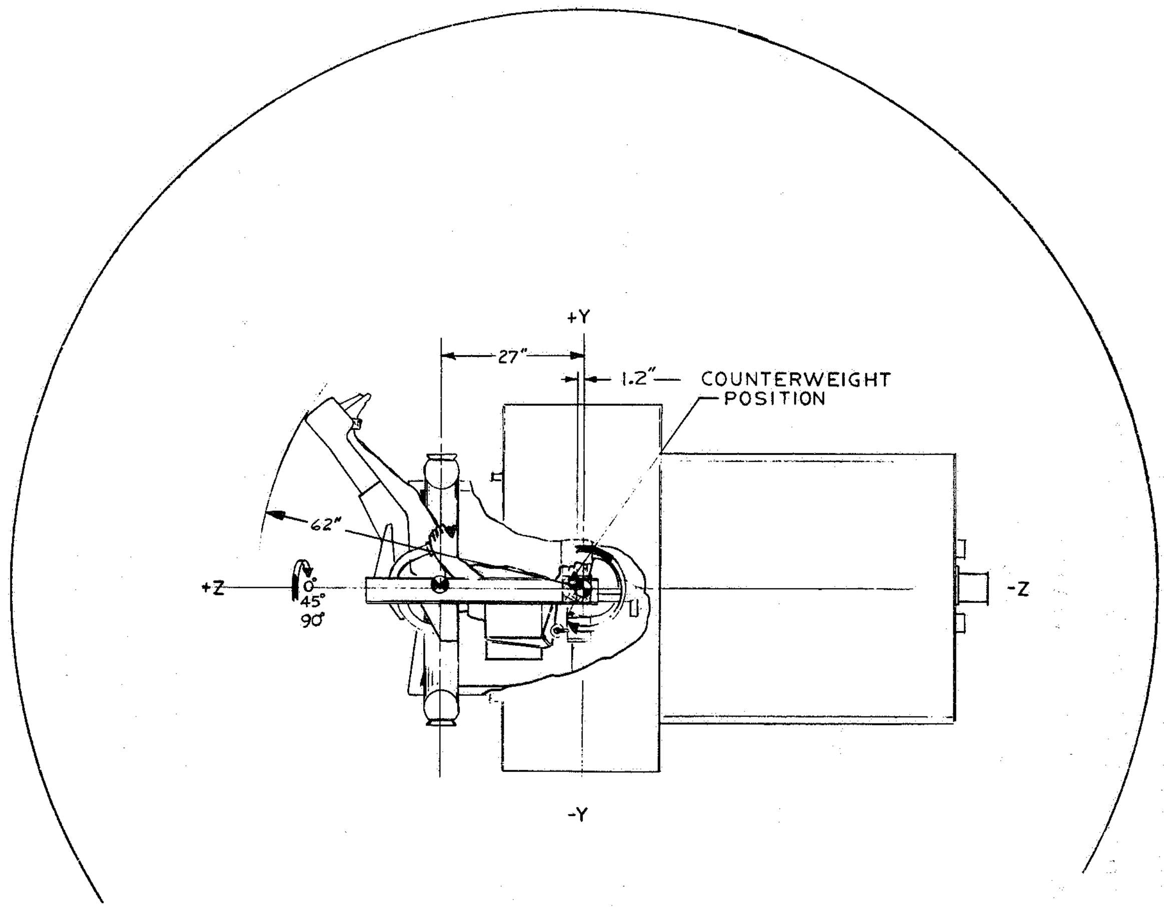


Figure 25. T-010E, Coupled Angular Velocities (Part 1)

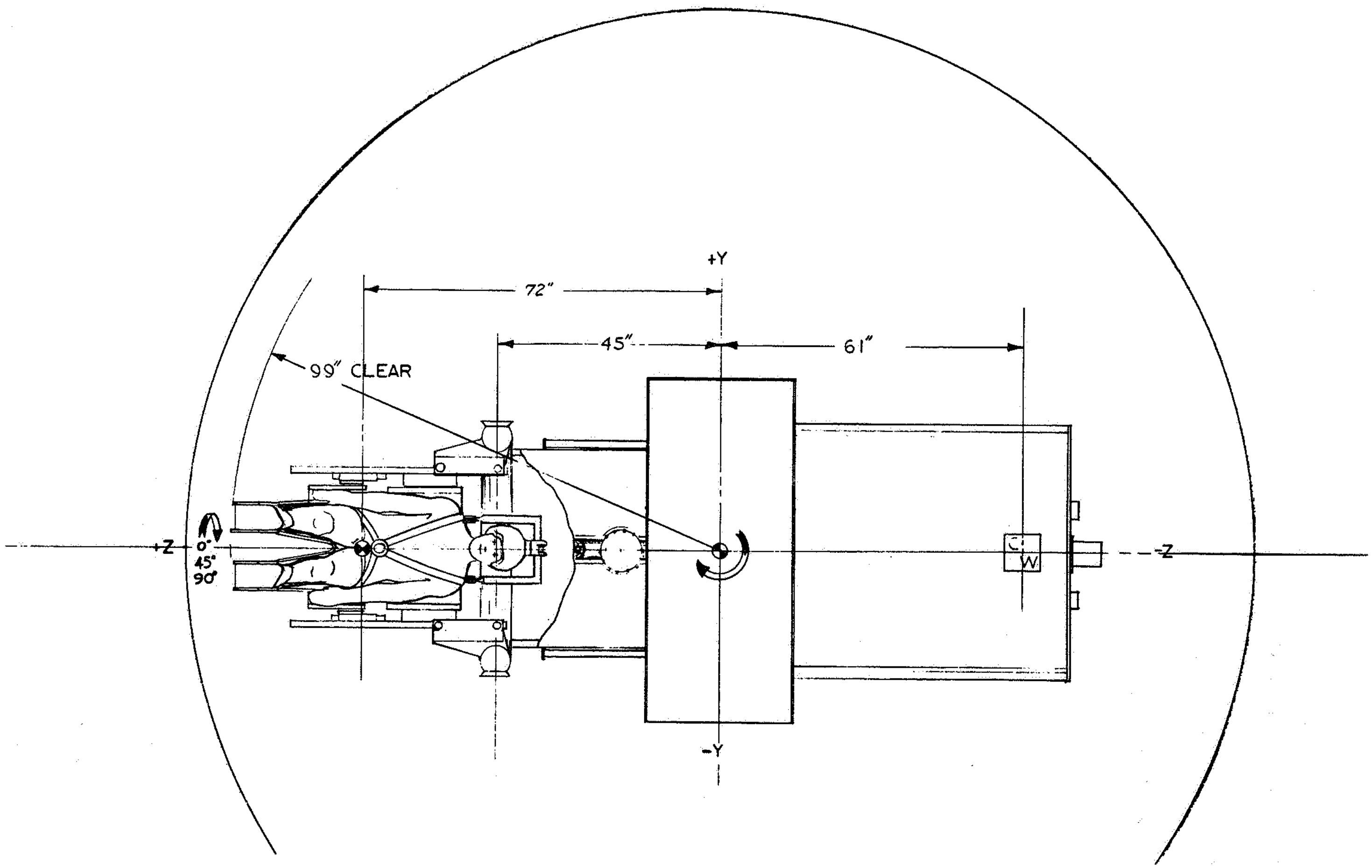


Figure 26. T-010E, Coupled Angular Velocities (Part 2)

Table 19. T-010E - Semicircular Canal Stimulation and Coupled Angular Velocities - Time Analysis

		MINUTES
Preparation:	get subject into couch	3
	adjust head restraint	10
	position legs up	2
	adjust and tighten straps	3
	install 1^{o} collimated light	15
	install response box	10
	rotate couch 90^{o} right about z axis (each orientation requires separate spin up)	2
	Translate arm to position head 45" from center of rotation.	2
	observer to console	5
	monitoring leads calibration	
	horizontal EOG	10
	vertical EOG	10
	head turn angle	3
	blood pressure	5
	EKG	3
	baseline performance	10
Experiment:	spin up (4 RPM @ 0.1 g/sec.)	1
	x axis head turns	10
	y axis head turns	10
	spin up (10 RPM @ 0.1 g/sec.)	1

Table 19. T-010E - Semicircular Canal Stimulation and Coupled Angular Velocities - Time Analysis (Cont'd)

	MINUTES
X axis head turns	10
Yaxis head turns	10
spin down	2
observer to centrifuge	5
arm translation head at center rotation	2
observer to console	5
spin up (4 RPM @ 0.1 g/sec.)	1
Xaxis head turns	10
Yaxis head turns	10
spin up (10 RPM @ 0.1 g/sec.)	1
Xaxis head turns	10
Yaxis head turns	10
spin down (-0.1 g/sec.)	1
observer to centrifuge	5
rotate couch 90^{0} left about Y axis with eyes in board	2
observer to console	5
spin up (4 RPM @ 0.1 g/sec.)	1
X axis head turns	10
Y axis head turns	10
spin down (-0.1 g/sec.)	2
observer to centrifuge	5

Table 19. T-010E - Semicircular Canal Stimulation and Coupled Angular Velocities - Time Analysis (Cont'd)

	MINUTES
spin up (4 RPM @ 0.1 g/sec.)	1
X axis head turns	10
Y axis head turns	10
spin up (10 RPM @ 0.1 g/sec.)	1
X axis head turns	10
Y axis head turns	10
spin down (-0.1 g/sec.)	2
observer to centrifuge	5
rotate couch 45° right about Z axis	2
observer to console	5
spin up (4 RPM @ 0.1 g/sec.)	1
X axis head turns	10
Y axis head turns	10
spin up (10 RPM @ 0.1 g/sec.)	1
X axis head turns	10
Y axis head turns	10
spin down (-0.1 g/sec.)	2
observer to centrifuge	2
translate arm to position head 45" from center rotation.	2
observer to console	5
spin up (4 RPM @ 0.1 g/sec.)	1

Table 19. T-010E - Semicircular Canal Stimulation and Coupled Angular Velocities - Time Analysis (Cont'd)

		MINUTES
	X axis head turns	10
	Y axis head turns	10
	spin down (0.1 g/sec.)	2
Clean up:	observer to centrifuge	5
	reorient couch and arm	4
	loosen straps	1
	loosen head restraint	3
	remove collimated light	10
	remove response box	10
	remove subject from couch	2

Table 20. Experimental Procedures:
T-010F - Threshold Levels of Sensitivity to Linear Acceleration

Subjects: 1, 2 and 3

Days of Test: (1) 2, 9, 30; (2) 2, 16, 37; (3) 2, 23, 44

Time Required: Preparation, 91 min.; Test, 189 min.; Clean up, 55 min.

Centrifuge Position: 45" to head from center of rotation

Couch Orientation: Facing tangential
tilt 15°, 30°, 45°
facing normal
legs full up

RPM: 14, 19.8, 28; Number Spin Ups Required: 24 (x 9)

Acceleration: 0.586 rad/sec.^{2}, 0.415 rad/sec.^{2}, 0.293 rad/sec.^{2}

g Onset: 0.1 g/sec.

g Requirements: 0.25 (HD), 0.50 (HD), 1.0 (HD)

Stability Required: yes

Experiment Instrumentation: eye photography equipment
EOG
remote camera switch
EVLH

Subject Preparation Required: bite bar
EOG
EKG

Data to be Recorded: degree of tilt in minutes
subject's indication of degree of tilt (EVLH)
counter-rolling (photography)

Possible Hazards: None

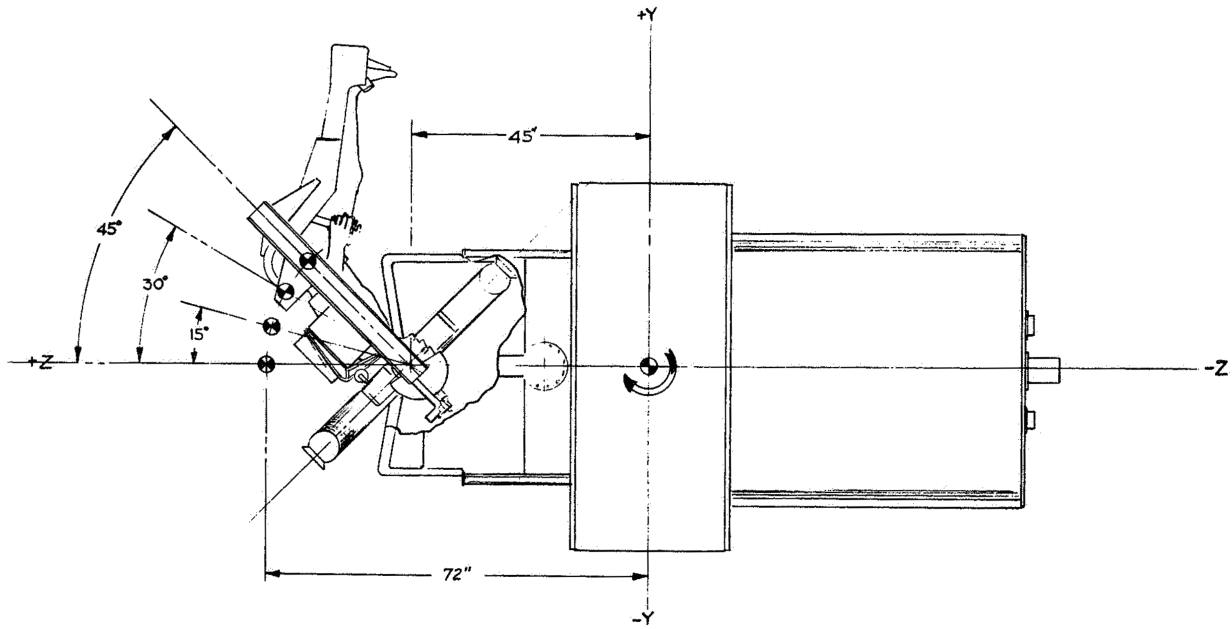


Figure 27. T-010F, Otolith "g" Sensitivity (Part 1)

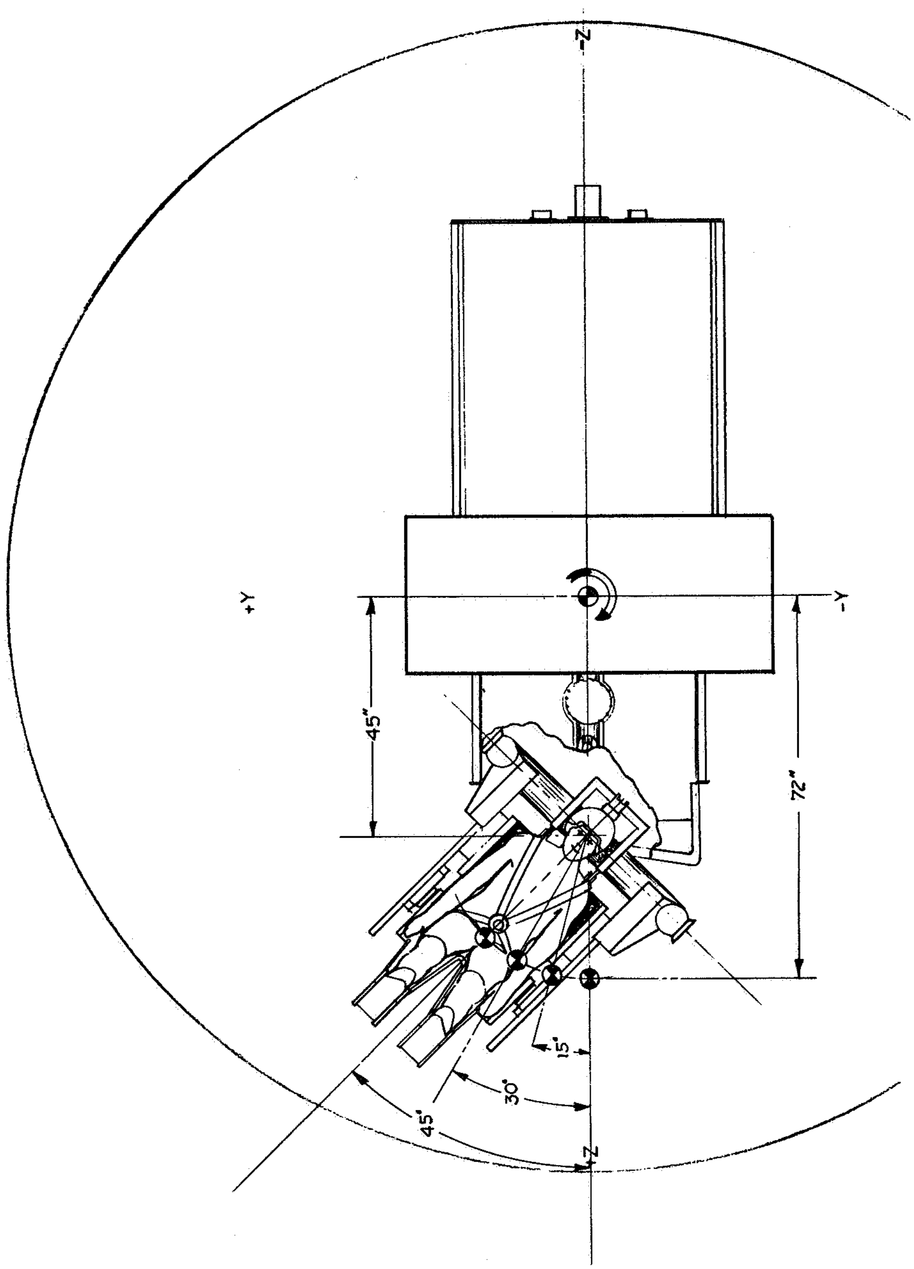


Figure 28. T-010F, Otolith "g" Sensitivity (Part 2)

Table 21. T-010F - Threshold Levels of Sensitivity to Linear Acceleration

Time Analysis

		MINUTES
Preparation:	get subject into couch	3
	adjust head restraint	10
	adjust and tighten straps	3
	install bite bar	10
	install eye camera	20
	install collimated horizontal line box	20
	rotate couch 90° right about Z axis	2
	arm translation - head 45" from center rotation	2
	observer to console	5
	monitoring leads calibration	
	EKG	3
	blood pressure	5
	tilt indicator	3
	eye camera calibration	5
Experiment: I	spin up (16 RPM)	1
	test	2
	spin up (22.5 RPM)	1
	test	2
	spin up (33.0 RPM)	1
	test	2
	spin down	3
	observer to couch	5
	couch orientation 15° about Y axis	2
	observer to console	5
	spin up (16 RPM)	1
	test	2
	spin up (22.5 RPM)	1

Table 21. T-010F - Threshold Levels of Sensitivity to Linear Acceleration Time Analysis (Cont'd)

	MINUTES
test	2
spin up (33.0 RPM)	1
test	2
spin down	3
observer to couch	5
couch orientation to 30° about	2
observer to console	5
spin up (16 RPM)	1
test	2
spin up (22.5 RPM)	1
test	2
spin up (33.0 RPM)	1
test	2
spin down	3
observer to couch	5
couch orientation to 45° about Y axis	2
observer to console	5
spin up (16 RPM)	1
test	2
spin up (22.5 RPM)	1
test	2
spin up (33.0 RPM)	1
test	2
spin down	3
observer to couch	5
orient couch to 0° Y axis	2

Table 21. T-010F - Threshold Levels of Sensitivity to Linear Acceleration

Time Analysis (Cont'd)

		MINUTES
Experiment: II	orient couch 90^{o} left about X axis	2
	observer to console	5
	spin up (16 RPM)	1
	test	2
	spin up (22.5 RPM)	1
	test	2
	spin up (33.0 RPM)	1
	test	2
	spin down	3
	observer to couch	5
	couch orientation 15^{o} about X axis	2
	observer to console	5
	spin up (16 RPM)	1
	test	2
	spin up (22.5 RPM)	1
	test	2
	spin up (33.0 RPM)	1
	test	2
	spin down	3
	observer to couch	5
	couch orientation to 30^{o} about X axis	2
	observer to console	5
	spin up (16 RPM)	3
	test	2
	spin up (22.5 RPM)	1
	test	2
	spin up (33.0 RPM)	1
	test	2

Table 21. T-010F - Threshold Levels of Sensitivity to Linear Acceleration

Time Analysis (Cont'd)

		MINUTES
Experiment: II	spin down	3
	observer to couch	5
	couch orientation to 45^{o} about X axis	2
	spin up (16 RPM)	1
	test	2
	spin up (22.5 RPM)	1
	test	2
	spin up (33.0 RPM)	1
	test	2
	spin down	3
	observer to couch	5
	orient couch to 0^{o} X axis	2
Clean up:	observer to centrifuge	5
	reorient couch	4
	loosen straps	1
	remove bite bar	10
	remove eye camera	20
	remove tilt response box	10
	loosen head restraint	3
	remove subject from couch	2

Table 22. Experimental Procedure:
T-010G - Re-entry Simulation

Subjects: 1

Days of Test: 7, 14, 21, 29, 35, 40

Time Required: Preparation, 45 min.; Test 11 min.; Clean up 27 min.

Centrifuge Position: couch center 76" from center of rotation

Couch Orientation: 78^{o} off radius

circumferential

RPM: 45; Number Spin Ups Required: 6

Acceleration: 0.108 rad/sec^2

g Onset: 0.1 g/sec

g Req: 4.37 (At subjects center of mass)

Stability Required: none*

Experiment Instrumentation: on-board computer

re-entry stimulator (PMTC)

blood pressure

Subject Preparation Required: EKG

blood pressure cuff

Data to be Recorded: performance score

heart rate

blood pressure

Possible Hazards: syncope

decreased re-entry tolerance.

*Keep cross-coupling below $60^{o}/sec^2$.

Table 23. T-010G - Re-entry Simulation - Time Analysis

		MINUTES
Preparation:	subject into couch	3
	adjust and tighten straps	3
	install PMTC	20
	rotate couch 90° left about X axis	2
	raise head 12° about Y axis	2
	observer to console	5
	monitoring leads calibration	
	EKG	3
	blood pressure	5
	activate computer	2
Experiment:	spin up	1
	computer program	8
	spin down	2
Clean up:	Observer to centrifuge	5
	reorient couch	4
	loosen straps	1
	remove PMTC	15
	remove subject from couch	2

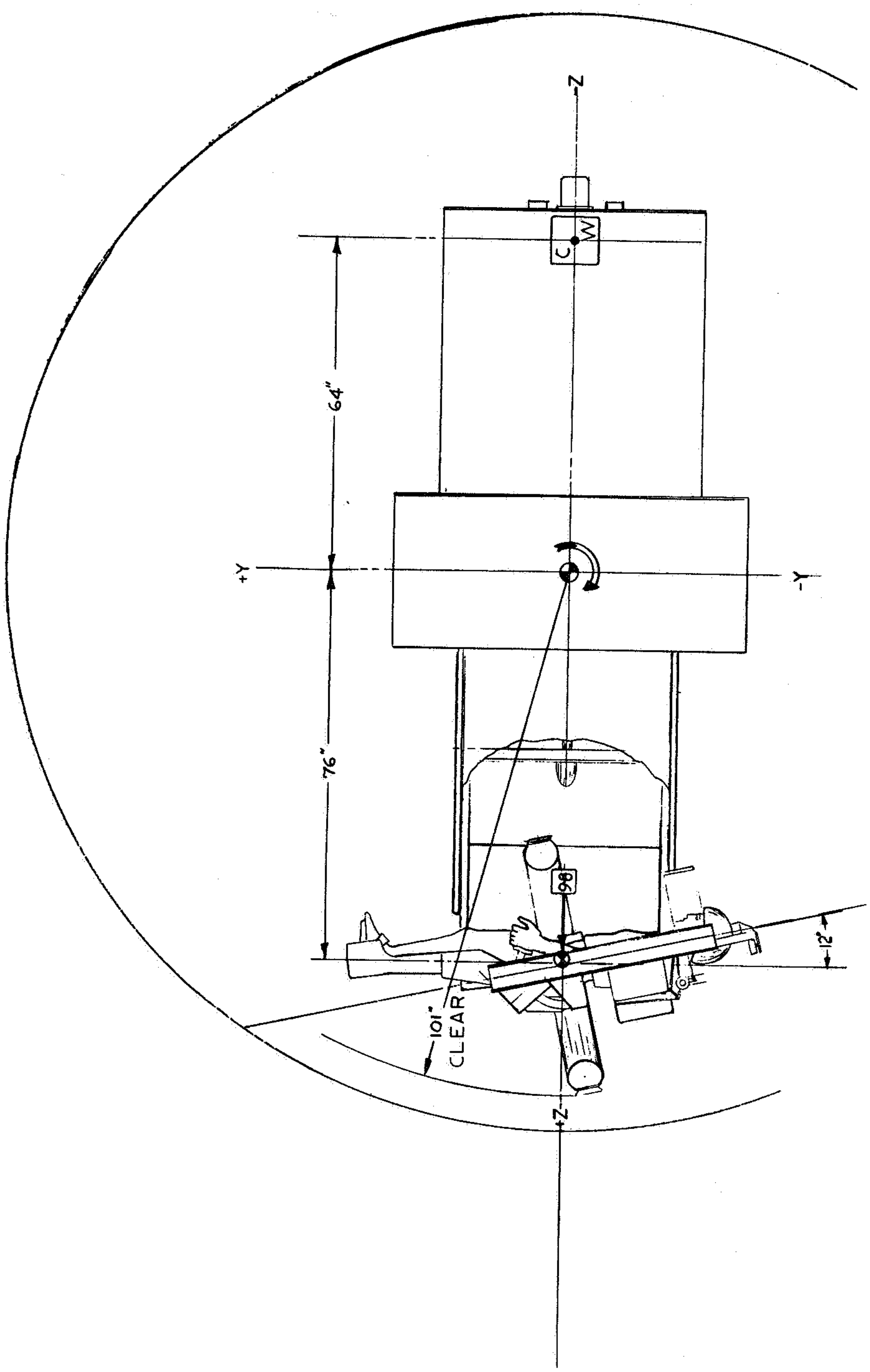


Figure 29. T-010G, Re-entry Simulation

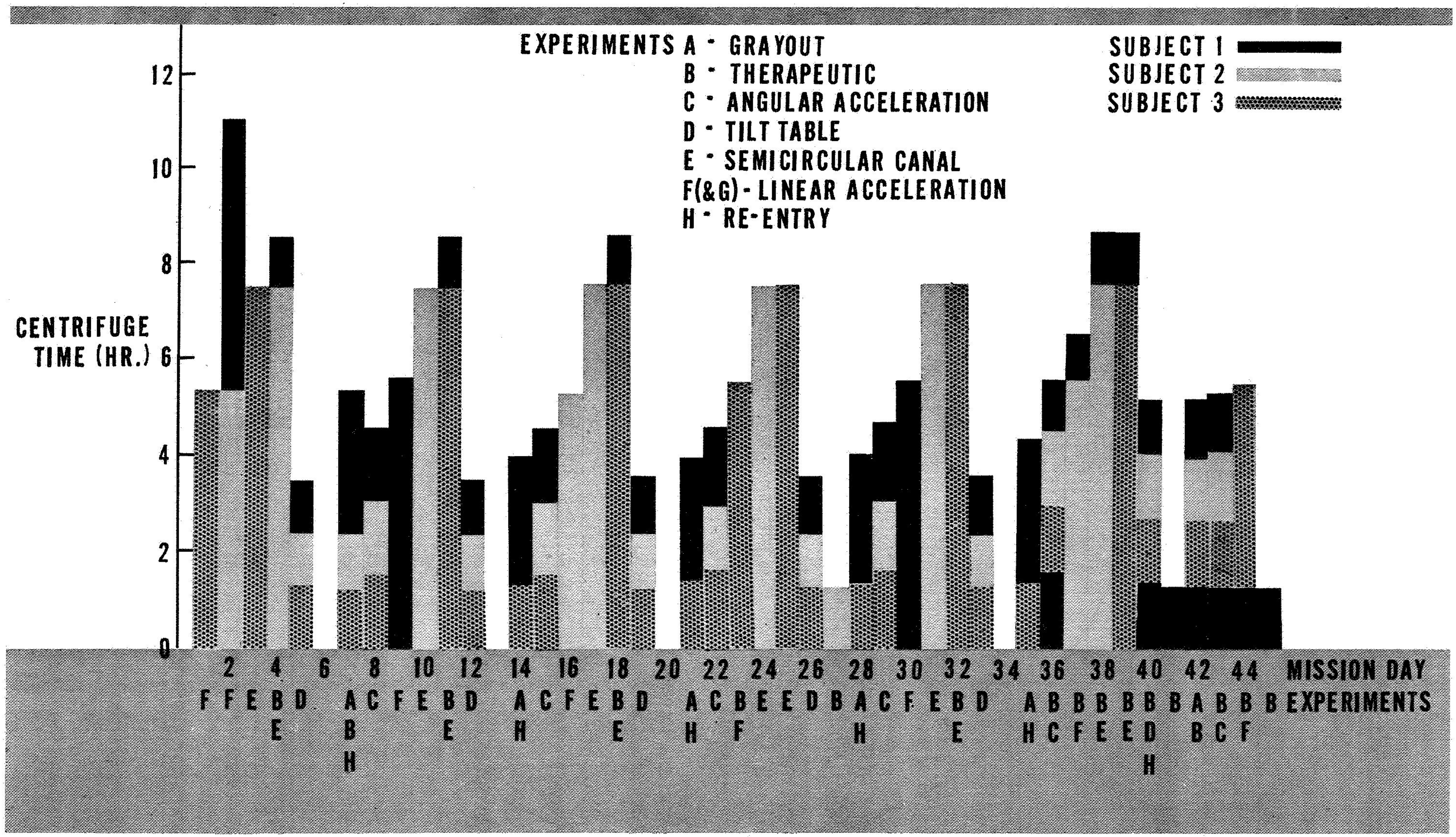


Figure 30 Time Utilization of Centrifuge-by Subject.

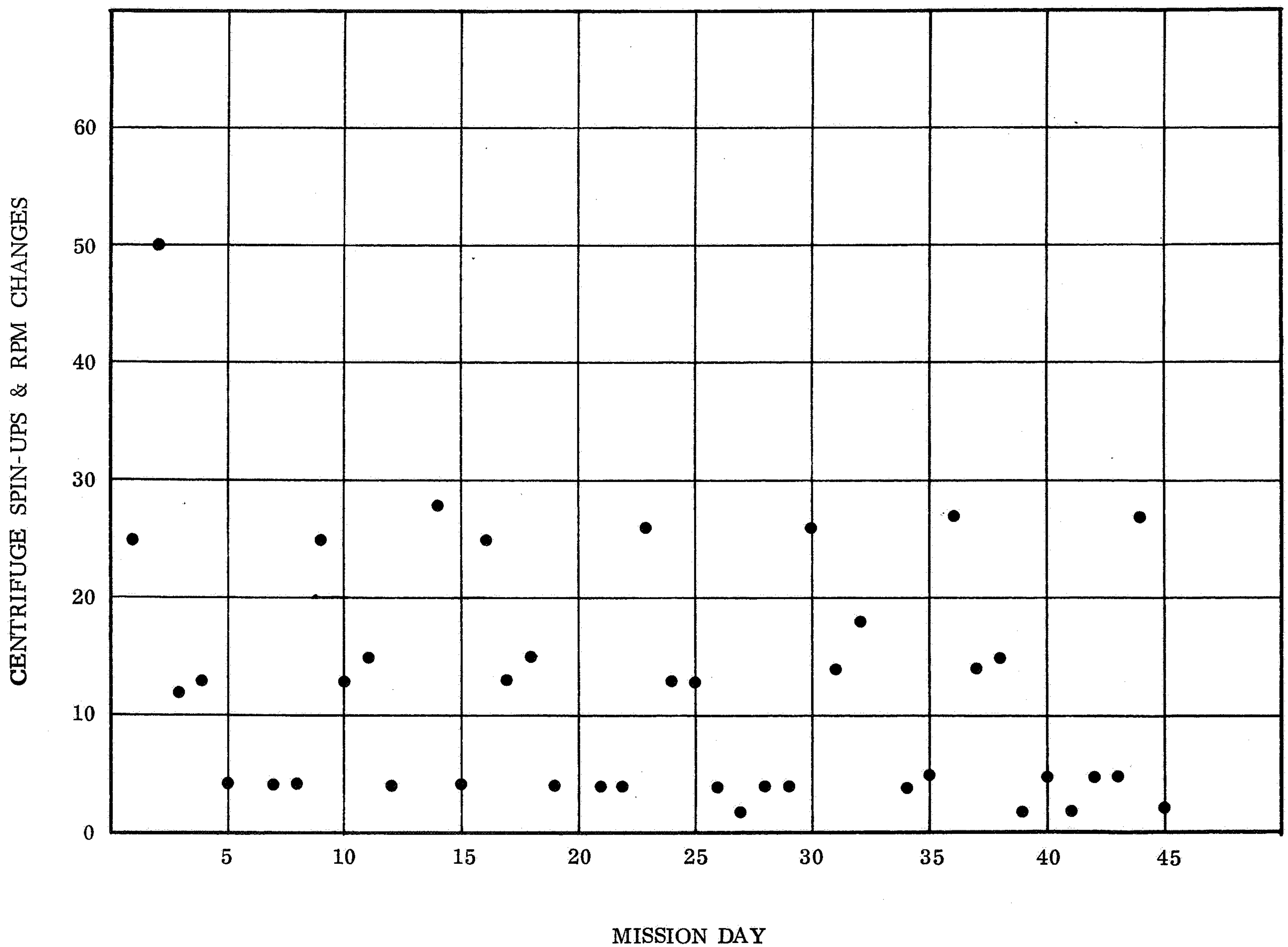


Figure 31. Number of Spin-ups and RPM Changes/Day for T-010 Experiments.

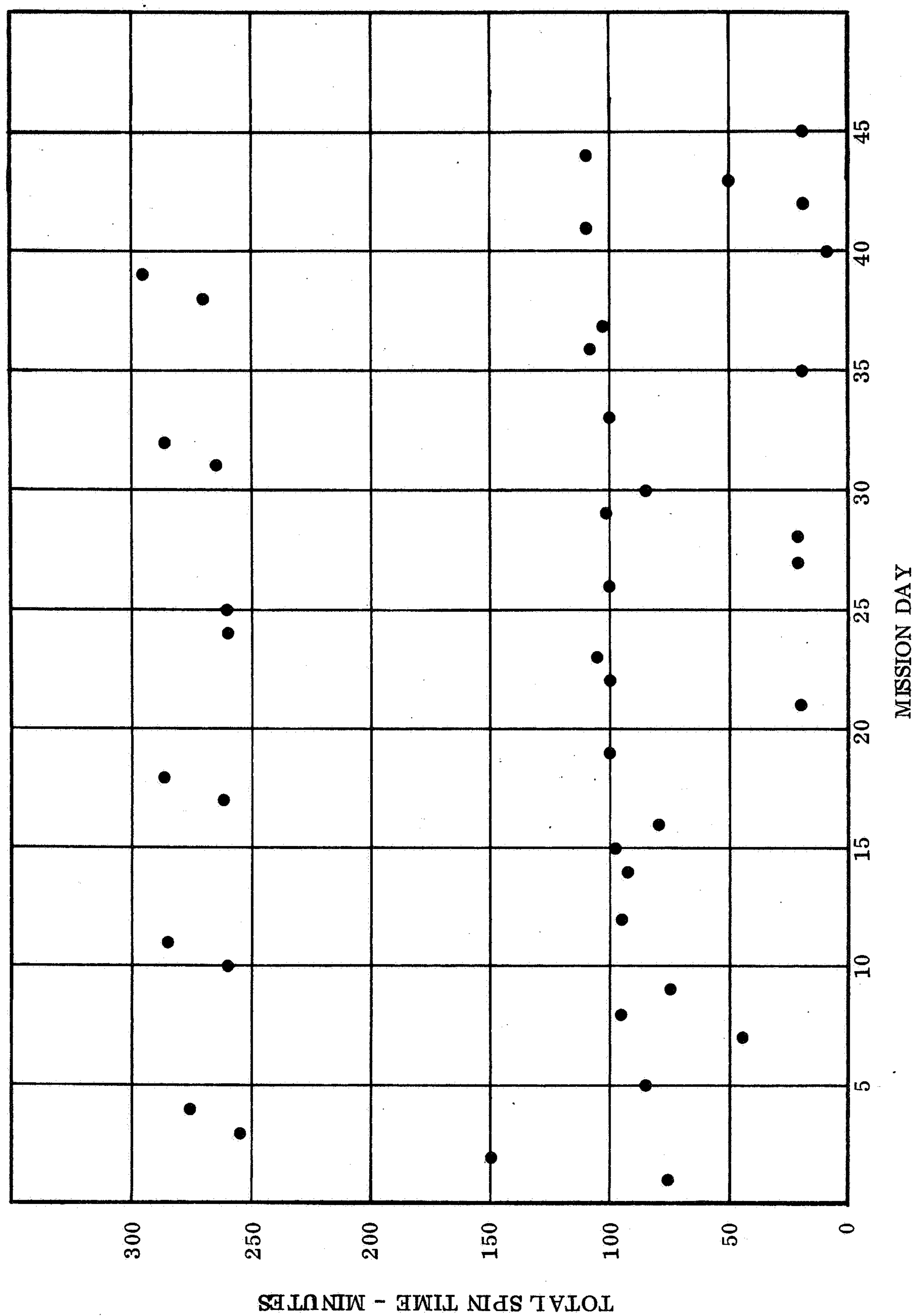


Figure 32. Total Time/Day of Centrifuge Spin

Total Time Required Per Experimental Mission Day

To determine the time requirement needed to accomplish the desired tasks in each mission day, the totals for each experiment were extended to each day in which they were to be performed. This allowed a total time per day analysis showing the time involvement for each subject. No attempt has been made to show which subject will act as observer as this choice will be mediated by other requirements of the mission. The combined data are shown in Table 24.

Total Utilization of The On-board Centrifuge on A Per Day Basis

The time requirements for each experiment differ as do the number of centrifuge spin ups. In order to visualize the total utilization of the centrifuge on a per day basis, it is necessary to separate these two functions. Figures 31 and 32 show a graphic presentation of these requirements.

Centrifuge Requirements To Fulfill T-010 Experiments

To determine the power requirements to fulfill T-010, the physical parameters of speed, acceleration, time and number of repetitions must be known for each experiment. For those experiments which require more than one rpm, it has been assumed that the lower rpm will be increased to the higher rpm without a spin down. Such an increase has been considered a separate spin up. The combined data are shown in Table 24.

Table 24. Centrifuge Requirements

EXPERIMENT	RPM	g REQ.**	g ONSET	RADIUS	ACCELERATION RAD/SEC.^{2}	TIME*	TOTAL SPIN UPS FOR MISSION
T-010A	47	6 ●	0.1 g/sec.	96"	.082	6 min.	12
T-010B	53	4 ●	0.1 g/sec.	51"	.139	20 min.	40
T-010C	0-6	NA	NA (Z axis rotation to 0.1° to 1.0°/sec.^{2})	27"	.0017 to .0175	30 min.	18
T-010D	Rot. 27 Tilt .375	1 ■	0.05 g/sec. NA	48"	.141 .0196	27 min. 2 sec.	18
T-010E	4	.025 ● .046 ●	0.1 g/sec.	56.5"	1.68 .91	20 min.	72
	10	.161 ● .278 ●	0.1 g/sec.	101.5"	.65 .37	20 min.	72
T-010F	14	.25 ○	0.1 g/sec.	45"	.586	3 min.	72
	19.8	.50 ○	0.1 g/sec.	45"	.415	3 min.	72
	28	1.0 ○	0.1 g/sec.	45"	.293	3 min.	72
T-010G	45	4.37 □	0.1 g/sec.	76"	.108	11 min.	6

* Time req'd to take each data point or series of points at a fixed observation level.

** Location of required g referenced to subject;

feet- ● ; heart- ■ ; head- ○ ; Center of Mass- □

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APPENDIX A

DUPLICATION OF EARTH HEMO-STATIC PRESSURE DISTRIBUTION ON AN ORBITAL CENTRIFUGE

The purpose of this report is to determine the extent to which the hemo-static pressure distribution associated with tilt table experiments on earth may be duplicated on an orbital centrifuge.

General expressions for the longitudinal pressure gradient are derived for fluid elements acted on by the earth gravitational field and the "effective gravitational" field produced by an orbiting centrifuge. Equating these expressions permits the derivation of a geometrical relationship between astronaut body length and centrifuge radius. Consideration of the physical situation allows certain boundary conditions to be imposed on this geometrical relationship. An interrelationship between the basic parameters (tilt angle, datum point location on body, radius to datum point, and datum point effective normal acceleration) results, which limits the range of cases which may be duplicated.

A typical earth tilt experiment is taken as an example problem and its solution is provided in the form of tabulated data and graphs.

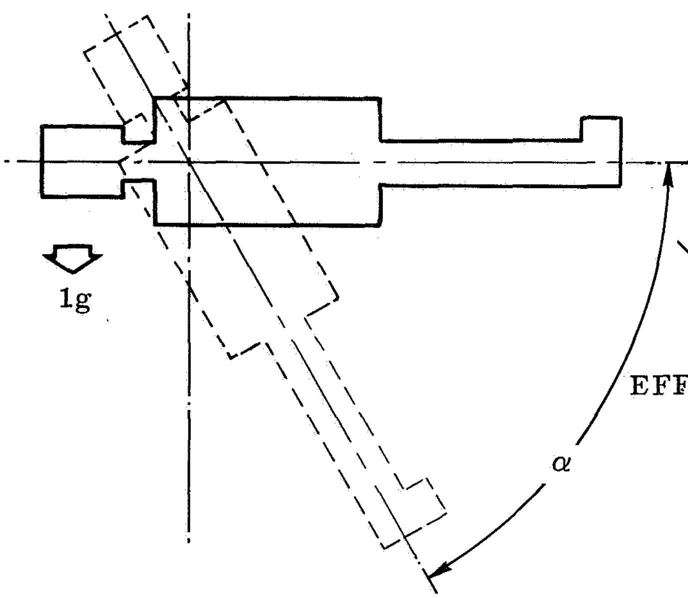


Figure A1. Earth Tilt.

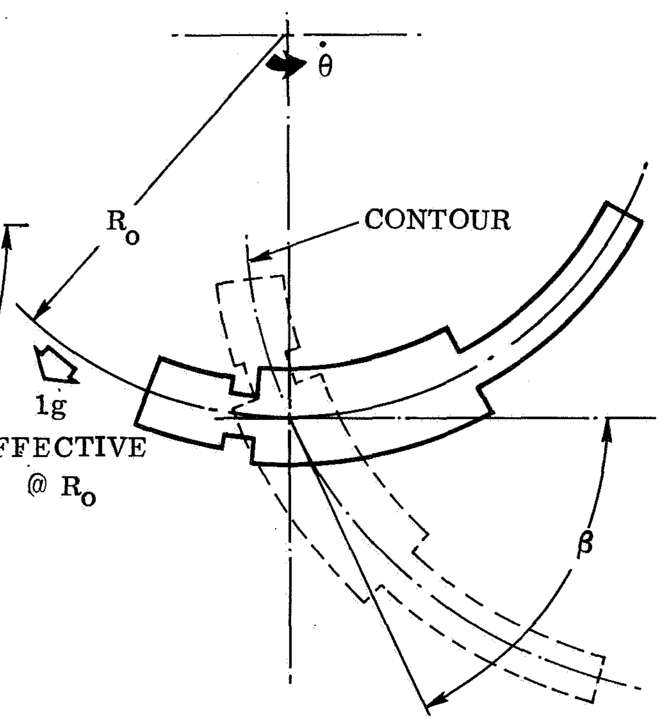


Figure A2. Orbital simulation.

A. DERIVATION OF EARTH TILT GRADIENT

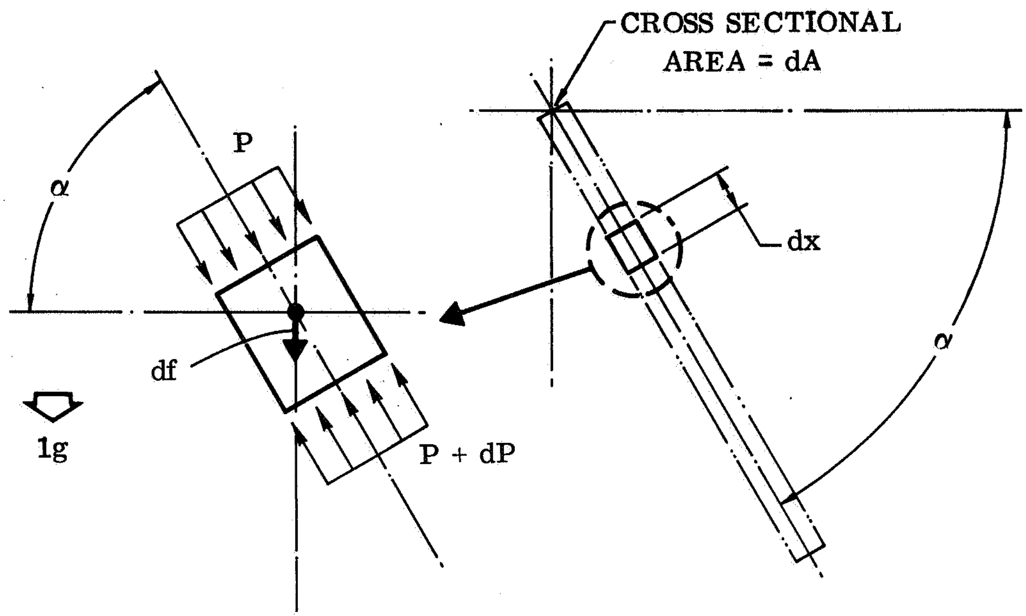


Figure A3. Typical element of fluid in a parallel force field.

From Figure A3:

$$df = dw = (g)\ dm$$
$$dm = \rho\, dv = \rho\ dx\ dA$$
$$df = \rho g\ dx\ dA$$

Then:

$$+\searrow \Sigma F_x = 0 = PdA + (df \sin\alpha) - (P+dP)\ dA$$
$$= \cancel{PdA} + (\rho g\ dx\ dA \sin\alpha) - \cancel{PdA} - dPdA$$

Or:

$$\rho g\ dx\ \cancel{dA} \sin\alpha = dP\ \cancel{dA}$$

Then:

$$\frac{dP}{dx} = \rho g \sin\alpha \quad (1)$$

B. DERIVATION OF GRADIENT DUE TO ROTATION

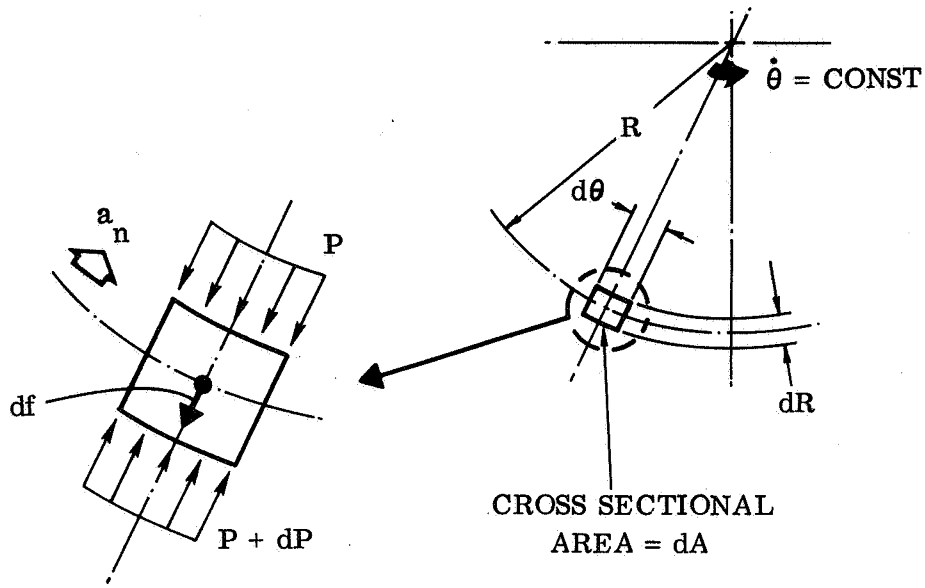


Figure A4. Typical element of fluid in a radial force field.

From Figure A4.

$$df = a_n \, dm$$

$$dm = \rho \, dR \, dA$$

$$a_n = R\dot{\theta}^2$$

$$df = (R\dot{\theta}^2) \rho \, dR \, dA$$

$$+\swarrow \Sigma F_R = 0 = PdA + df - (P + dP) \, dA$$
$$= \cancel{PdA} + R\dot{\theta}^2 \rho \, dR \, dA - \cancel{PdA} - dP \, dA$$

Or:

$$\rho\dot{\theta}^2 \, RdR\cancel{dA} = dP \, \cancel{dA}$$

Then:

$$\frac{dP}{dR} = \rho\dot{\theta}^2 R \qquad (2)$$

C. SETTING THE GRADIENTS EQUAL

Select a baseline radius, R_o, to some convenient datum point, x_o, where a given normal acceleration, a_{n_o}, is required.

Then: $a_{n_o} = R_o \dot{\theta}^2$ Or: $\dot{\theta}\ (\text{const}) = \sqrt{a_{n_o}/R_o}$

Also:

$$\frac{dP}{dx} = \frac{dP}{dR}\ \frac{dR}{dx} \tag{3}$$

Thus:

$$\cancel{\rho} g \sin \alpha = \cancel{\rho} \dot{\theta}^2 R \frac{dR}{dx} \qquad \text{Or:} \quad \left(\frac{g \sin \alpha}{\dot{\theta}^2} \right) dx = RdR$$

But:

$$\dot{\theta}^2 = a_{n_o}/R_o \qquad \text{Then:} \quad \frac{\dot{\theta}^2}{g} = \frac{a_{n_o}^*}{R_o}$$

Where $a_{n_o}^*$ is given in "g's"

Or: $g/\dot{\theta}^2 = R_o/a_{n_o}^*$

Then: $$\frac{g \sin \alpha}{\dot{\theta}^2} = \frac{R_o \sin \alpha}{a_{n_o}^*}$$

Let:

$$\frac{\sin \alpha}{a_{n_o}^*} = K \qquad \text{Then:} \quad \frac{g \sin \alpha}{\dot{\theta}^2} = KR_o$$

Then:

$$KR_o\, dx = RdR \qquad \text{Or:} \quad \frac{dR}{dx} = K \left[\frac{R_o}{R} \right] \tag{4}$$

And:

$$KR_o \int dx = \int RdR \qquad \text{Then:} \quad KR_o x = \frac{R^2}{2} + C$$

Let:

$$x = 0 \text{ at } R = R_o$$

Then:

$$0 = \frac{R_o^2}{2} + C \qquad \text{Or:} \quad C = \frac{-R_o^2}{2}$$

Then: $$KR_o\, x = \frac{R^2}{2} - \frac{R_o^2}{2} = \frac{R^2 - R_o^2}{2}$$

Or: $$x = \frac{R^2 - R_o^2}{2KR_o} \tag{5}$$

Alternately:

$$R^2 = 2KR_o x + R_o^2 \quad \text{(From Eq. (5))}$$

Then:

$$R = \sqrt{2KR_o x + R_o^2} \tag{6}$$

Observation:

If x_o is taken at any point on the body axis other than the top of the head, then the x coordinate can take negative values. From Eq. (6):

$$\sqrt{2KR_o x + R_o^2} = \sqrt{R_o\,(2Kx + R_o)}$$

Thus, a negative value for the expression in parentheses will result in an imaginary radius, which will not satisfy the physical problem.

Then:

$$(2Kx + R_o) \geqslant 0 \quad (= 0 \text{ in the limiting case})$$

Or:

$$x \geqslant -R_o/2K \qquad \text{Or:} \quad R_o \geqslant -2Kx \tag{7}$$

Then, for a given datum point, x_o, a given normal acceleration, $a_{n_o}{}^*$, and a given earth tilt, α, R_o <u>cannot</u> be selected arbitrarily but, rather, must satisfy the inequality (7).

D. INCLINATION OF A FLUID ELEMENT TO ITS LOCAL TANGENT

Ref. Eq. (4):

$$\frac{dR}{dx} = \frac{K\,R_o}{R} = \sin\beta \leqslant 1.0$$

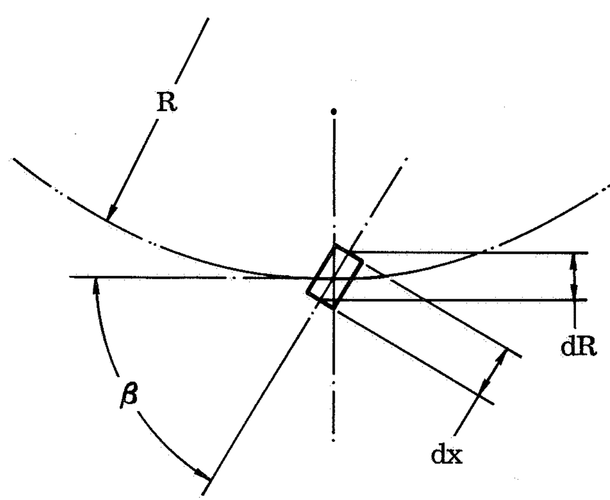


Figure A5. Typical non-radial fluid element.

Observations

1. dx is a fixed length (i.e., very small but inelastic), hence the maximum value of $dR \equiv dx$ since, from Figure A5.

$$\sin \beta_{max} \equiv 1.0 = \frac{dR_{max}}{dx} \quad (8)$$

To satisfy Eq. (8) a given element must be radial, hence the limiting orientation at the innermost end of the fluid column (i.e., top of the subjects head) is radial. This satisfies the fixed length (inelastic) requirement.

2. The following relationship results from above and Eq. (4)

$$\frac{KR_o}{R} \leqslant 1.0 \quad (9)$$

Since a particular value of $a_{n_o}{}^*$ will be specified at some point x_o on the body, R_o will exceed R for body points radially inward from the datum point. (The inward direction is the area of concern since it is in this direction only where the potential problems of "elasticity" and "imaginary radius" occur).

From inequality (9) a limitation on allowable values of K is obtained.

$$K \leqslant \frac{R}{R_o} \leqslant 1.0 \quad \text{(inward from } x_o\text{)}$$

Hence $K < 1.0$ for all cases except x_o at the top of the head with radial orientation at that point. Therefore:

$$K \equiv \frac{\sin \alpha}{a_{n_o}{}^*} \leqslant 1.0$$

Hence, the only earth tilt cases which may be duplicated are those whose baseline parameters satisfy the following inequality:

$$\sin \alpha \leqslant a_{n_o}{}^* \quad (10)$$

3. For a given permissible value of K it is possible to establish a relationship between x and R_o by treating R_o as a variable whose minimum value is desired.

Ref. Eq. (4): $\frac{dR}{dx} = K \frac{R_o}{R}$

For $R_{o_{min}}$: $\frac{dR}{dx} = 1.0$

Then: $K \frac{R_{o_{min}}}{R_{min}} = 1.0$ Or: $R_{min} = KR_{o_{min}}$

From Eq. (5): $x_{min} = \frac{R_{min}^2 - R_{o_{min}}^2}{2KR_{o_{min}}}$

Then:

$$x_{min} = \frac{(KR_{o_{min}})^2 - R_{o_{min}}^2}{2KR_{o_{min}}} = \frac{R_{o_{min}}^2 (K^2-1)}{2KR_{o_{min}}} =$$

$$= \frac{R_{o_{min}} (K^2-1)}{2K}$$

Or: $$R_{o_{min}} = \frac{2Kx_{min}}{K^2-1} \quad (11)$$

E. EXAMPLE PROBLEM (PREFERRED EARTH TILT CASE FOR ORBITAL SIMULATION).

Parameters:

$\alpha = 70^{o}$ Then $\sin \alpha = .940$

$a_{n_o}^* = 1.00$ g

$K = \frac{\sin \alpha}{a_{n_o}^*} = \frac{.940}{1.00} = .940$

Let datum be heart, then: $x_{min} \cong -1.5$ ft.

Solution:

$$R_{o_{min}} = \frac{2Kx_{min}}{K^2 - 1} = \frac{(2)(.940)(-1.5)}{.940^2 - 1} = 24.3 \text{ ft.}$$

Therefore: Cannot duplicate this case on the postulated space research centrifuge except with 1g approx. at the top of the head since 2 Ft $< R_o <$ 5 Ft.

F. ALTERNATE CASE

Since from example problem K = .940 < 1.00, the tilt angle and g-level are compatible per (10). Then, let $x_{min} = 0$ (i.e., datum point at top of head):

From (11): $$R_{o_{min}} = \frac{2Kx_{min}}{K^2 - 1} = 0$$

But: Cannot get 1g @ $R_o = 0$.

Then: Since minimum g-variation along body will provide best simulation, find R_o for low g-variation at reasonable rotational speed.

From (6): $R = \sqrt{2KR_o x + R_o^2}$, And: $\Delta g \propto \Delta R$ $\quad \Delta R = R_{max} - R_o$

$$a_{n_o}{}^* = \frac{R\dot{\theta}^2}{32.2} = 1.0 \quad \text{or:} \quad \dot{\theta} = \sqrt{32.2/R_o} \quad \frac{\text{Rad}}{\text{Sec}}$$

Then: $$\dot{\theta}^* = \frac{60}{2\pi}\sqrt{\frac{32.2}{R_o}} = 9.55 \sqrt{32.2/R_o} \text{ RPM} \qquad \text{(F-1)}$$

Then: $$R = \sqrt{(2)(.940) R_o (6) + R_o^2} = \sqrt{11.28 R_o + R_o^2} \qquad \text{(F-2)}$$

Table A1. Solution of equations (F-1) and (F-2).

① R_o	② 11.28 x①	③ ①^2	④ ②+③	⑤ $\sqrt{④}$= R	⑥ ⑤-①	⑦ 32.2/ ①	⑧ $\sqrt{⑦}$	⑨ 9.55 x⑧= $\dot{\theta}^*$
0.5	5.64	0.25	5.89	2.43	1.93	64.4	8.02	76.6
1.0	11.28	1.0	12.28	3.51	2.51	32.2	5.67	54.2
1.5	16.92	2.25	19.17	4.38	2.88	21.5	4.64	44.3
2.0	22.56	4.0	26.56	5.15	3.15	16.10	4.01	38.3
2.5	28.20	6.25	34.45	5.86	3.36	12.88	3.59	34.3
3.0	33.84	9.0	42.84	6.55	3.55	10.73	3.28	31.3
3.5	39.48	12.25	51.73	7.19	3.69	9.20	3.03	28.9
4.0	45.12	16.0	61.12	7.81	3.81	8.05	2.84	27.1
4.5	50.76	20.25	71.01	8.42	3.92	7.16	2.68	25.6
5.0	56.40	25.0	81.40	9.01	4.01	6.44	2.54	24.3

From the table, Col. ⑥, it is apparent that low values of R_o result in low increments in R from head to toe, hence low variation in G along the length of the body. However, Col. ⑨ also indicates that high rotation rates are associated with low values of R_o. Due to clearance requirements in the hub area of the centrifuge a minimum radius of approximately 2.0 ft. is available. The corresponding ΔR is 3.15 ft. and $\dot{\theta}^* = 38.3$ rpm.

From Col. ⑦: $\dot{\theta}^2 = 16.10 \text{ rad/sec}^2$

From Col. ⑤: $R_{max} = 5.15$ ft.

$$G_{max} = (R_{max}\dot{\theta}^2)/32.2 = (5.15)(16.10)/32.2 = 2.57 \text{ G's}$$

$\Delta G = 2.57 - 1.00 = 1.57$ from head to toe.

G. DERIVATION OF COORDINATES AND CURVE PLOTS

NOTE: Section D is concerned with the inclination of an element in the spin plane of the centrifuge. The same equations hold for an element in a radial plane normal to the spin plane. For plotting purposes, the non-orthogonal R and x coordinates used thus far are clumsy, hence polar coordinates R and θ will be used for the "in-plane" plot (Figure A8) and rectangular coordinates R and Z will be used for the "normal-plane" plot (Figure A9).

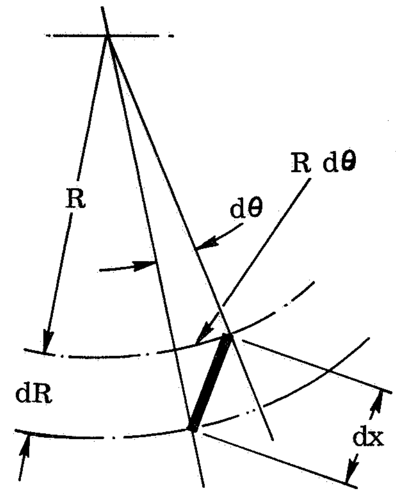


Figure A6. Typical increment of length.

Derivation of Coordinates:

1. Polar (R, θ)

$$(dx)^2 = (dR)^2 + (Rd\theta)^2$$

$$\frac{(dx)^2}{(dR)^2} = \left(\frac{R}{KR_o}\right)^2 = \frac{(dR)^2 + R^2\,(d\theta)^2}{(dR)^2}$$

$$\left(\frac{1}{KR_o}\right)^2 R^2\,(dR)^2 = (dR)^2 + R^2\,(d\theta)^2$$

$$\left[\left(\frac{1}{KR_o}\right)^2 (R^2) - 1\right](dR)^2 = R^2\,(d\theta)^2$$

Or:

$$\left(\frac{1}{KR_o}\right)^2 \left[\frac{R^2 - (KR_o)^2}{R^2}\right] (dR)^2 = (d\theta)^2$$

$$d\theta = \left(\frac{1}{KR_o}\right) \frac{\sqrt{R^2 - (KR_o)^2}}{R}\, dR$$

Or:

$$\theta = \frac{1}{KR_o} \int \frac{\sqrt{R^2 - (KR_o)^2}}{R}\, dR$$

Then:

$$\theta = \left(\frac{1}{KR_o}\right)\left[\sqrt{R^2 - (KR_o)^2} - (KR_o)\cos^{-1}\left(\frac{KR_o}{R}\right) + C\right]$$

Letting $\theta = 0$ @ $R = R_o$:

$$0 = \sqrt{R_o^2 - (KR_o)^2} - KR_o \cos^{-1}(K) + C \qquad C = R_o\left(K\cos^{-1}(K) - \sqrt{1 - K^2}\right)$$

Then:

$$\theta = \frac{1}{KR_o}\left\{\sqrt{R^2 - (KR_o)^2} - KR_o\cos^{-1}\left(\frac{KR_o}{R}\right) - R_o\left(\sqrt{1-K^2} - K\cos^{-1} K\right)\right\} \quad (12)$$

For $R_o \doteq 2.00$ and $K = .940$: $KR_o = 1.880$; $(KR_o)^2 = 3.535$;

$K^2 = .884$; $1-K^2 = .116$; $\sqrt{1-K^2} = .340$; $\cos^{-1}(.940) = 20^o = .349$ rad.

$K \cos^{-1} K = (.940)(.349) = .328$; $1/KR_o = 1/1.880 = .532$

$$\theta = .532\left\{\sqrt{R^2 - 3.535} - 1.880 \cos^{-1}\left(\frac{1.880}{R}\right) - 2.00\ (.012)\right\} \tag{12A}$$

Table A2. **Solution of Eq. 12A for Figure A8.**

① R	② ①^2 = R^2	③ ②-3.535	4 $\sqrt{③}$	⑤ $\frac{1.880}{①}$	⑥ $\cos^{-1}$⑤	⑦ $\frac{\pi}{180}$x⑥	⑧ 1.880 x⑦	⑨ ④-⑧	⑩ ⑨x.024	⑪ .532x⑩
1.5	2.250	-1.285	--	--	-- --	--	--	--	.--	--
2.0	4.000	0.465	.682	.940	20^o	.349	.656	.026	0.002	~0.000
2.5	6.250	2.715	1.650	.752	41.2^o	.719	1.350	0.300	0.276	.146
3.0	9.000	5.465	2.34	.627	51.1^o	.892	1.677	0.663	0.639	.340
3.5	12.250	8.715	2.95	.537	57.5^o	1.003	1.886	1.064	1.040	.553
4.0	16.000	12.465	3.53	.470	62.0^o	1.081	2.035	1.495	1.471	.782
4.5	20.250	16.715	4.09	.418	65.3^o	1.140	2.143	1.947	1.923	1.022
5.0	25.000	21.465	4.63	.376	67.95^o	1.184	2.225	2.405	2.381	1.266
5.5	30.250	26.715	5.16	.342	70^o	1.221	2.295	2.875	2.851	1.515

Derivation of Coordinates

2. Rectangular (R, Z)

$$(dx)^2 = (dz)^2 + (dR)^2$$

$$\frac{(dx)^2}{(dR)^2} = \left(\frac{R}{KR_o}\right)^2 = \frac{(dz)^2 + (dR)^2}{(dR)^2}$$

$$\left(\frac{1}{KR_o}\right)^2 R^2 (dR)^2 = (dz)^2 + (dR)^2$$

$$\left[\left(\frac{1}{KR_o}\right)^2 (R^2) - 1\right](dR)^2 = dz^2$$

$$\left(\frac{1}{KR_o}\right)^2 \left[R^2 - (KR_o)^2\right](dR)^2 = dz^2$$

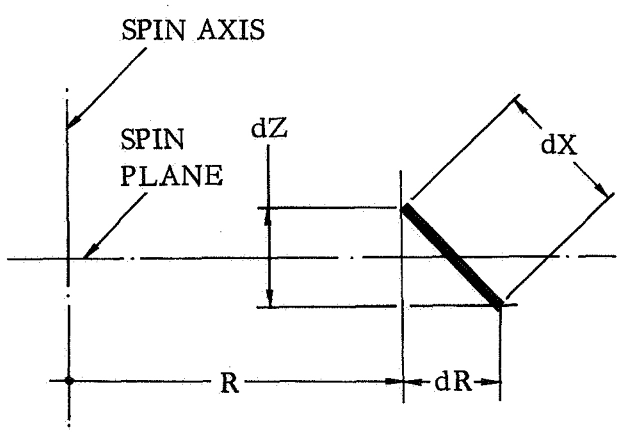


Figure A7. Typical increment of length.

Or: $dz = \left(\frac{1}{KR_o}\right)\sqrt{R^2 - (KR_o)^2}\ dR$

Then: $$Z = \left(\frac{1}{KR_o}\right)\int\sqrt{R^2 - (KR_o)^2}\ dR = \frac{1}{2KR_o}\left[R\sqrt{R^2-(KR_o)^2} - (KR_o)^2 \ln\left(R + \sqrt{R^2-(KR_o)^2}\right) + C\right] \tag{13}$$

Then, let $Z = 0$ @ $R = R_o$

$$0 = R_o \sqrt{R_o^2 - (KR_o)^2} - (KR_o)^2 \ln (R_o + \sqrt{R_o^2 - (KR_o)^2} + C$$

$$C = -R_o^2 \sqrt{1 - K^2} + KR_o^2 \ln \left[R_o (1 + \sqrt{1 - K^2}) \right]$$

$$= R_o^2 \left\{ -\sqrt{1 - K^2} + K \ln \left[R_o (1 + \sqrt{1 - K^2}) \right] \right\} = (4.00) \left\{ -.340 + .940 \ln(2.680) \right\}$$

$$= 4.00 \left\{ -.340 + .926 \right\} = (4.00)(.586) = 2.344$$

$$\text{Then: } Z = \frac{.532}{2} \left[R\sqrt{R^2 - 3.535} - 3.535 \ln (R + \sqrt{R^2 - 3.535}) + 2.344 \right] \tag{13A}$$

Table A3. **Solution of Eq. 13A for Figure A9.**

① R	② ①^2 = R^2	③ ② - 3.535	④ $\sqrt{③}$	⑤ ①x④	⑥ ①+ ④	⑦ ln ⑥	⑧ 3.535x⑦	⑨ ⑤-⑧	⑩ ⑨+ 2.344	⑪ .266 x ⑩
2.0	4.00	0.465	.682	1.364	2.682	.985	3.48	-2.116	0.228	.061
2.5	6.25	2.715	1.650	4.125	4.150	1.422	5.03	-0.905	1.439	.383
3.0	9.00	5.465	2.34	7.020	5.34	1.674	5.92	+1.10	3.444	.916
3.5	12.25	8.715	2.95	10.32	6.45	1.862	6.59	3.73	6.074	1.615
4.0	16.00	12.465	3.53	14.120	7.53	2.020	7.14	6.98	9.324	2.480
4.5	20.25	16.715	4.09	18.40	8.59	2.150	7.60	10.80	13.144	3.495
5.0	25.00	21.465	4.63	23.350	9.63	2.265	8.01	15.34	17.684	4.70
5.5	30.25	26.715	5.16	28.40	10.66	2.365	8.36	20.04	22.384	5.95

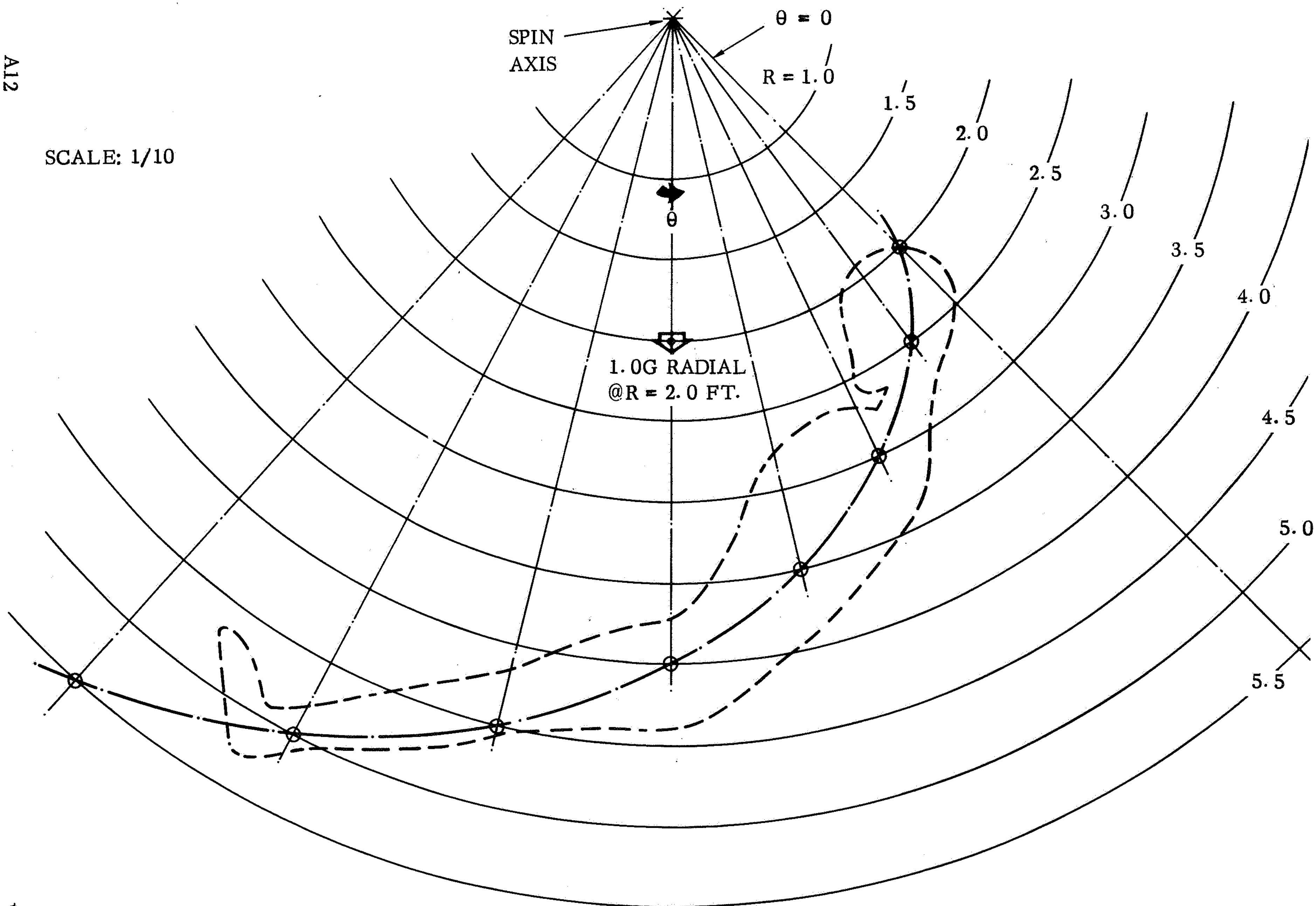


Figure A8. Required body axis curvature in spin plane to duplicate pressure gradient of 70° earth tilt.

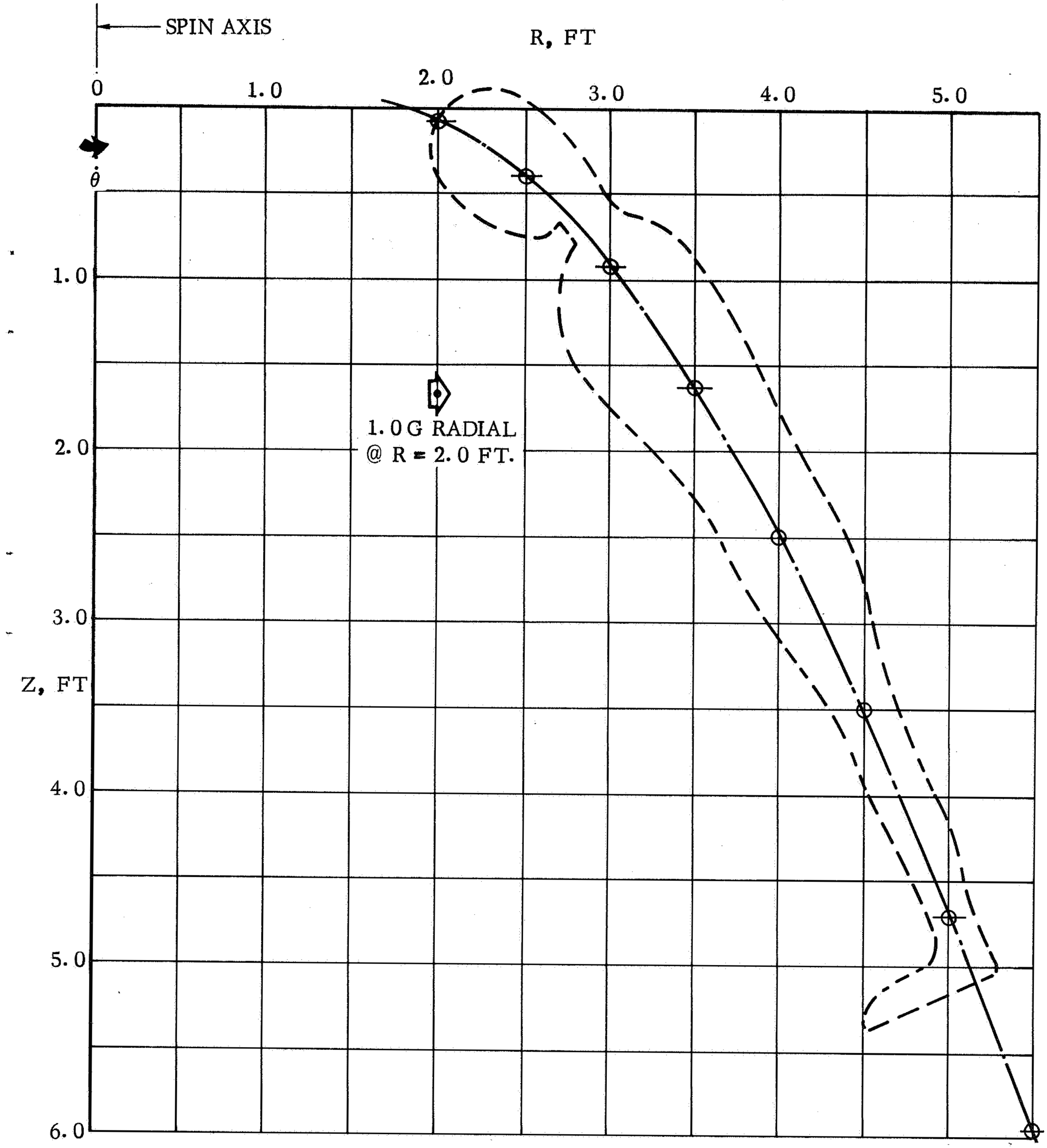
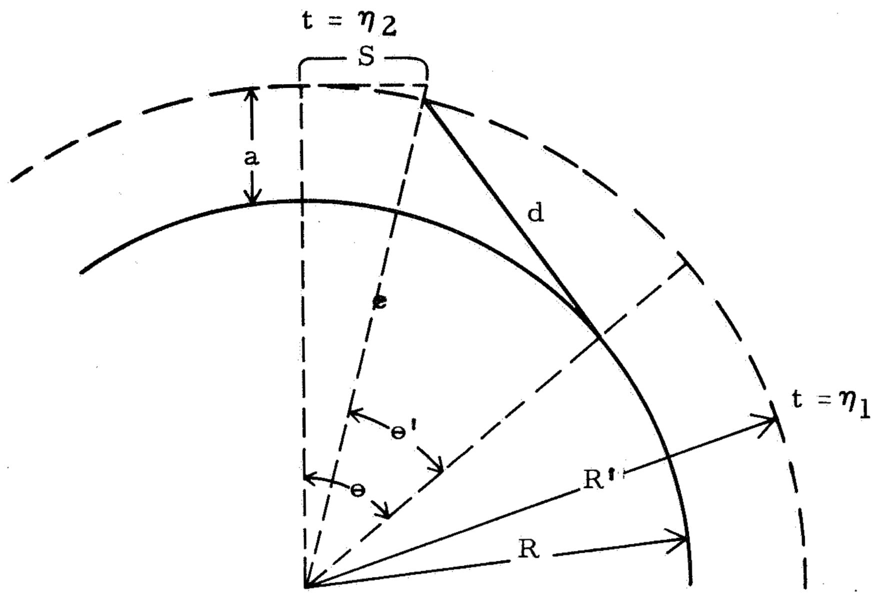


Figure A9. Required body axis curvature in normal plane to duplicate pressure gradient of 70° earth tilt.

APPENDIX B

TRAJECTORY OF FECES AFTER SEPARATION



t = time, seconds
R = length from pivot point of centrifuge to seat bottom = 6.41 ft
R' = length from pivot point of centrifuge to collector bottom = 7.16 ft
S = distance from centerline of collector to position of feces at $t = \eta_2$, ft
d = distance feces travels from $t = \eta_1$ to $t = \eta_2$, ft
θ = angle through which centerline of collector passes from $t = \eta_1$ to $t = \eta_2$, radians
θ' = angle through which feces passes from $t = \eta_1$, to $t = \eta_2$, radians
ω = angular speed, radians per second
v = velocity, ft per second
ϕ = angle between the centerline of the canister and the path of the feces, degrees
e = radial distance between center of spin and the feces, ft
a = collector depth, ft

The velocity of the seat and the separated feces is given by:

$$v_{seat} = v_{feces} = \omega R \tag{1}$$

The distance that the feces travels from the moment of separation ($t = \eta_1$) until it strikes the collector bottom ($t = \eta_2$) is:

$$d = v \text{ feces } t \tag{2}$$

substituting from equation 1

$$d = \omega R t$$

but the distance d is also given by

$$d = \sqrt{e^2 - R^2} \tag{3}$$

the magnitude of e is

$$e = \sqrt{S^2 + R^2} \tag{4}$$

combining equations 3 and 4

$$d = \sqrt{S^2 + R^2 - R^2} \tag{5}$$

The distance from the collector centerline that the feces strikes can be found from the relation

$$S = (\theta - \theta') R' \tag{6}$$

the angle is given by

$$\theta = \omega t$$

but ωt is also equal to $\frac{d}{R}$ so

$$\theta = \frac{d}{R}$$

the angle θ' is given by $\theta' = \tan^{-1} \omega t = \tan^{-1} \frac{d}{R}$

substituting for θ and θ' in equation 6

$$S = \left(\frac{d}{R}\right) R' \tag{7}$$

substituting equation 5 in equation 7, gives

$$S = \left(\frac{\sqrt{S^2 + R'^2 - R^2}}{R} - \tan^{-1} \frac{\sqrt{S^2 + R'^2 - R^2}}{R} \right) R'$$

The value of S is then determined by assuming a value of S, substituting it in both sides of equation 8. When the correct value of S has been assumed, both sides of the equation will be equal.

Sample Calculation:

$R = 6.41$ ft, $R' = 7.16$ ft, $a = 3/4$ ft

$$S = \left[\frac{\sqrt{S^2 + R'^2 - R^2}}{R} - \tan^{-1} \frac{\sqrt{S^2 + R'^2 - R^2}}{R} \right] R'$$

assume $S = 0.30$ ft

$$0.30 = \left[\frac{\sqrt{0.09 + 51.2 - 41.2}}{6.41} - \tan^{-1} \frac{\sqrt{10.09}}{6.41} \right] 7.16$$

$$0.30 = \left[\frac{3.175}{6.41} - \tan^{-1} -.496 \right] 7.16$$

$$0.30 = \left[0.496 - 26.4 \times \frac{2\pi}{360} \right] 7.16$$

$$0.30 = \left[0.496 - 0.461 \right] 7.16$$

$$0.30 \neq 0.25$$

try $S = 0.25$

$$0.25 = \left[\frac{\sqrt{0.063 + 10}}{6.41} - \tan^{-1} \frac{\sqrt{10.063}}{6.41} \right] 7.16$$

$$0.25 = \left[\frac{3.175}{6.41} - \tan^{-1} 0.495 \right] 7.16$$

$$0.25 = 0.035 \times 7.16$$

$$0.25 = 0.25$$

So the correct answer is $S = 0.25$ ft or 3 inches.

ABSTRACT

This document is a portion of the final report prepared under Contract NAS 1-7309, Feasibility Study of a Centrifuge Experiment for the Apollo Applications Program. The contract was performed for the Langley Research Center, National Aeronautics and Space Administration, Hampton, Virginia. The complete final report consists of the following documents:

NASA CR-66649 GDC-DCL-68-001 (SRC-AN-703	Volume I	Space Research Centrifuge Configuration, Installation and Feasibility Studies
NASA CR-66650 GDC-DCL-68-002 (SRC-SD-604)	Volume II	Specification and Test Requirements - Space Research Centrifuge Engineering Development Prototype
NASA CR-66651 GDC-DCL-68-003 (SRC-MS-112)	Volume III	Experimental Requirements for the Space Research Centrifuge
GDC-DCL-68-004 (SRC-MS-302)	Volume IV	Manned Centrifuge Test Report

This study examines the application of an on-board centrifuge as a versatile research tool for the measurement of human physiological responses in the space environment. A realistic orbital centrifuge is configured based on a specified series of experiments dealing primarily with vestibular and cardiovascular physiology. Experiment feasibility is established in terms of spacecraft stability, reliability, safety, economics, weight, power and other influential factors. A ground based prototype of the orbital machine is defined and the required test program outlined. The effects of cross-coupled angular accelerations induced by the interaction of the astronaut/machine/vehicle motions is examined by a series of ground centrifuge tests with human subjects.